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# **DESIGN OF A DIGITAL COMPRESSION TECHNIQUE FOR SHUTTLE TELEVISION**

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SEPTEMBER 1976**

PREPARED FOR  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
LYNDON B. JOHNSON SPACE CENTER  
HOUSTON, TEXAS 77058

**TRW**  
DEFENSE AND SPACE SYSTEMS GROUP

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# ***DESIGN OF A DIGITAL COMPRESSION TECHNIQUE FOR SHUTTLE TELEVISION***

## **FINAL REPORT**

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**SEPTEMBER 1976**

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## 1. INTRODUCTION

The objective of this investigation is the determination of the performance and hardware complexity of data compression algorithms applicable to color television signals. The results obtained are used to assess the feasibility of digital compression techniques for Shuttle communications applications.

The investigation of digital compression techniques has been completed and the desired results have been obtained. For return link communications, the study has shown that a non-adaptive Two Dimensional DPCM Technique compresses the bandwidth of Field-Sequential Color TV to about 13 MBPS and requires less than 60 watts of secondary power. For forward link communications, a facsimile coding technique is recommended which provides high resolution slow scan television on a 144 KBPS channel. The on-board decoder requires about 19 watts of secondary power.

### 1.1 BACKGROUND

Recent advances in digital communication systems have led satellite-to-ground communications systems to take advantage of the greater efficiency and superior error control of digital communications. Television, however, has continued to utilize less efficient analog signalling techniques because of its large bandwidth requirements. The Shuttle orbiter has requirements for both uplink and downlink television via the Tracking Data Relay (TDRS) satellite link. The TDRS links impose design limitations on the Shuttle TV systems. Thus it is highly desirable, both for improved performance and as a contingency, to implement the Shuttle television links with more efficient digital signalling systems.

Developments in digital television coding techniques have established that significant compression of digital television data can be achieved at moderate cost, while maintaining extremely low distortion. This is done by exploiting the high degree of spatial, temporal, and spectral correlation in color video data. Most of these algorithms require substantial amounts of memory and high computational rates. However, with the advent of high-speed digital logic, a much greater degree of signal processing is possible at reasonable cost, size, weight, and power. These new technologies make possible the development of relatively sophisticated data compression systems which promise to bring the digital transmission of Shuttle television into the same bandwidth regime as analog.

The objective of the current study is to assess the feasibility of utilizing digital compression techniques for television signals in Shuttle communications applications. The early Shuttle missions are scheduled to fly a converted Apollo color television system. This system will use a black-and-white camera which is converted to field-sequential color by the addition of a rotating color wheel. The bandpass of the camera is 4.5 MHz which requires sampling the video signal at a minimum rate of 10 Msps. Assuming a minimum of 6-bits per sample, the system requires about 60 Mbps

for downlink data transmission. Since it is anticipated that the Shuttle will switch to a standard three-color NTSC television system in the future, the bandwidth requirement would be about 130 Mbps. The goal is to reduce the required data rates of the two systems by a factor of 5 to 10 while limiting spatial, spectral, and temporal distortions to levels acceptable to an average viewer.

By taking advantage of the high degree of correlation in both the spatial and temporal domains, the bandwidth of the video data can be reduced. A number of coding (i.e., data compression) algorithms that exploit these correlations have been developed in recent years. Efficient coding of the color television signal requires using sequential color fields in the field-sequential camera system to generate the usual (Y) illuminance and the chromaticity components (I, Q). This involves on-board preprocessing of the data and results in additional weight and power above that of other realtime television applications. In the NTSC television system, the color composite signal must be demodulated to generate Y, I, Q components prior to the application of a bandwidth compression method.\*

In addition to downlink color television transmission, slow scan black and white television signals will be sent from the ground station to the Shuttle. Slow frame rates, coupled with efficient coding of the television signals, can be utilized to transmit high resolution television signals over the 144 KBPS channel.

## 1.2 STUDY TASKS

The objective of the study is to simulate and evaluate practical digital television compression techniques applicable to the television signals used by Shuttle.

Two television systems are considered: 1) one system transmits high-quality color video in either field-sequential or standard NTSC TV format and 2) the other system transmits high resolution slow scan television over a small bandwidth channel.

### Task 1. System Definition and Analysis

In this task, specific characteristics of the two television systems are defined in coordination with the JSC technical monitor. All parameters and operational considerations pertinent to designing and simulating the video compression techniques are defined. These include sampling rates, grey-level resolution, dynamic range, data rates, frame and field formats, color structure and any constraints imposed by the communication system.

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\*Demodulation of the color composite signal can be avoided by modifying the cameras such that the video signals from individual cameras are available directly.

Based upon the system characteristics, candidate algorithms are selected for compressing the Shuttle field-sequential color video signal to achieve a 10-20 Mbps rate. Where feasible, the impact and compatibility of these algorithms are explored when used on NTSC color TV. However, selection of the compression technique favors the field-sequential system as it is the current Shuttle baseline and offers the greatest uncertainty in compression performance. At least one interframe and one intraframe coding technique, which utilize spectral correlation within the color signal, are included. Emphasis is placed upon a simple implementation approach that achieves a performance plateau in the 10 to 20 Mbps range within the Shuttle weight and power constraints.

Two methods of intraframe (single frame) coding are selected for compressing the high resolution slow scan television signals. Intraframe techniques are emphasized due to the lack of frame-to-frame correlation in slow scan systems and to afford maximum flexibility in the input signal accommodated. Special consideration are given to techniques which allow simple decoding (for on-board application) at the expense of more complex encoding. The selection considers the full range of currently known intraframe compression methods relying heavily on our recent performance and implementation studies. Single field simulation will be used to aid the selection process as deemed necessary.

#### Task 2. Compression Technique Evaluation

The most promising candidate algorithms for both systems are simulated on a digital computer. These algorithms are used to experiment with the following data sets:

- 1) A number of fields, sufficient to study both spectral and temporal characteristics, selected from the field-sequential color television video tape supplied by NASA.
- 2) A set of 2-3 frames of high resolution slow scan television data digitized from the NASA provided video tapes.

The simulation results are used to compare and optimize the various algorithms for each category. The mean square error and signal-to-noise ratio, as well as subjective quality of the compressed data as viewed on a Comtal image display, are used in selecting and optimizing the best technique in each category. By iteratively simulating and comparing the candidate algorithms, parameters of each are optimized and minimum acceptable bit rates established. A Dicomed (D40) filmwriter is used to produce both black and white and color hard-copy prints for side-by-side comparison of the original and compressed forms of the above data sets using the selected techniques.

Hardware and software implementations of each candidate algorithm are considered. The objective is to design an on-board bandwidth compression system feasible for Shuttle's use including a goal to fall within a 20 pound/20 watt weight/power envelope. The final design incorporates limitations specified by the NASA/JSC technical monitor

to make the system compatible with other Shuttle requirements. Design details are provided including block diagrams, flow charts, parts counts and weight and power estimates.

### Task 3. Final Algorithm Selection and Demonstration

Upon approval by NASA/JSC, the best algorithm emerging from Task 2 in each category is simulated on a digital computer and performance is evaluated using the following inputs:

- 1) The data base for the field-sequential color signals is 600 fields of digitized data sampled at a resolution of 512 samples per line and 525 lines per frame. This corresponds to 10 seconds of data on the video tape supplied by NASA/JSC.
- 2) The data base for the high resolution slow scan television signal consists of about 10 frames of data digitized from a representative slow scan system.

The bandwidth compressed data of the field-sequential system is converted to video tape and will be displayed on the modified SONY monitor at NASA/JSC to compare its quality with that of the original signal.

### 1.3 SUMMARY OF RESULTS

The study considered the feasibility of using image bandwidth compression techniques to reduce the bandwidth of Shuttle television. The TV systems considered in the study are Field-Sequential and NTSC color TV systems for downlink transmission and a slow scan high resolution system for uplink transmission. For each system a bandwidth compression technique is recommended and its preliminary design is investigated.

For Field-Sequential color TV two different techniques are recommended. One is an intraframe coding technique that uses a 2D-DPCM loop to encode individual fields directly. This reduces the bandwidth of the Field-Sequential color TV signal to 24 Mbps and requires 27 watts of secondary power for its operation. The encoder requires 85 integrated circuits (IC's). The second is an interframe coding technique that exploits spectral, temporal, as well as spatial correlation of the Field-Sequential color TV signal. This reduces the bandwidth of Field-Sequential color TV system to 13 Mbps and requires less than 60 watts of power for its operation. Its preliminary design requires about 348 IC's.

The recommended technique for NTSC color TV system utilizes spectral as well as spatial correlation of the data. It reduces the bandwidth of NTSC color TV to 28 Mbps using a 2D-DPCM loop and requires 30 watts of power for its operation. Its preliminary design requires less than 100 IC's.

The slow-scan uplink TV requires a distortion-free bandwidth compression system. The recommended technique for compressing the bandwidth of uplink system uses a two-dimensional HCK code. It reduces the bandwidth of the slow-scan system by about 3 to 1. The decoder for the recommended system requires 19 watts and 102 IC's.

The recommended techniques approach the imposed weight-power goals and produce high fidelity imagery. The performance of the recommended techniques were evaluated via simulation and the results demonstrate that the recommended techniques can be used to compress the bandwidth of Shuttle TV system while providing high fidelity reconstructed imagery.

## 2. DESCRIPTION OF SHUTTLE TELEVISION SYSTEMS

In this section both field-sequential and NTSC color television systems are described; then demodulation of these signals, which must be performed prior to their bandwidth compression, is discussed. Finally, the attributes of the slow-scan uplink system are described.

### 2.1 FIELD-SEQUENTIAL COLOR TELEVISION SYSTEM

The proposed space Shuttle color television system uses a color camera which is basically a black-and-white camera. It has been converted to a field-sequential color camera by the addition of a rotating color wheel. This technique is very similar to the old CBS field-sequential system developed for color television in the early 1940's. This system was characterized by the use of color band filters at the camera and again at the receiver, with only one camera necessary for viewing a scene and only one picture tube needed at the receiver. The Shuttle camera, like the old CBS camera, employs a color filter wheel to produce a serial color signal.

The field-sequential system uses a rotating filter wheel to expose the camera's image tube sequentially at the desired broadcast scan rate to the red, blue, and green components of a scene. Thus the need for complex optical paths and color registration adjustment, such as required in commercial color cameras, is eliminated. This enables the color camera to be lightweight and to require very little power. In addition, it is capable of operating in a large dynamic range of light levels. Since the output of a field-sequential system is in serial red-blue-green form, it is not compatible with present broadcast standards. This requires that a ground station color converter be utilized to change the sequential color signal to the standard parallel National Television System Committee (NTSC) color TV format so it can be rebroadcast by commercial stations.

A diagram of the color television system<sup>(1)</sup> is shown in Figure 2-1. The image is focused by a zoom lens through the color filter wheel onto the faceplate of the image tube. To simplify the problem of synchronization, the scan rate of the wheel as the color filters pass in front of the image tube must be the same as that of the TV networks, which is 60 fields per second. This is achieved by dividing the wheel into six sections, with the colors arranged in red-blue-green, red-blue-green order, and by driving the wheel at 10 revolutions per second. The motor speed is held constant by the timing of the camera's sync generator.

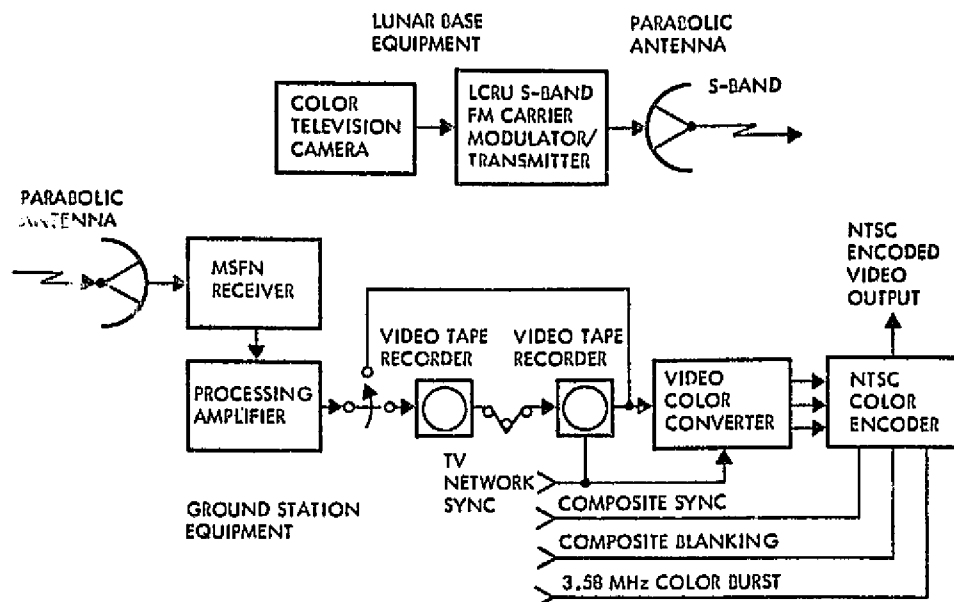


Figure 2-1. Apollo Color Television System

The field-sequential color signal, which is transmitted by an S-band transmitter (for Apollo), is picked up and amplified by a receiver at the receiving station. The signal is then clamped in a processing amplifier to restore the dc component and reestablish the average light value of the reproduced image.

The processed signal is placed into a series of two tape recorders for the purpose of compensating for doppler shift and presenting realtime information. The sequential color signal is then put into the scan converter that changes the video from the serial color format to the parallel (simultaneous) color format. The scan color converter is a storage and readout device holding the two previous fields in memory and presenting the three fields at once at the output of the incidence of the third field. As the new field is placed into the memory, the oldest field is erased, updating the information at the field rate. Thus, the three colors are simultaneously read out in the same manner as the output from a standard three-tube NTSC color camera. After video color conversion, the signal is sent to an NTSC color encoder which processes it to form the composite video signal.

## 2.2 NTSC COLOR TELEVISION SYSTEM

Most cameras generate three primary color signals: red, green, and blue, which are subsequently converted into a luminance and two chrominance components. The luminance signal, given by the equation

$$Y = 0.30R + 0.11B + 0.59G \quad (2.1)$$

contains the black-and-white information in the picture, while the two chrominance components, which are essentially the two difference signals (R-Y) and (B-Y), contain the color information. The advantage of this representation is compatibility

with black-and-white signals, and the fact that the chrominance components are of much lower bandwidth than the luminance signal. In the NTSC system two other chrominance axes are used, defined by

$$\begin{aligned} I &= 0.74 (R-Y) - 0.27 (B-Y) \\ Q &= 0.48 (R-Y) - 0.41 (B-Y) \end{aligned} \quad (2.2)$$

The reason for this choice is that the Q signal has a lower bandwidth than the (R-Y) and (B-Y) signals. Finally, a composite signal is formed by quadrature modulating the two chrominance signals onto a carrier at 3.579 MHz and adding them to the luminance signal. Thus,

$$M(t) = Y(t) + I(t) \cos(\omega_c t + 33^\circ) + Q(t) \sin(\omega_c t + 33^\circ) \quad (2.3)$$

where the angle 33 degrees corresponds to a displacement with respect to the reference color burst signal.

Subjective results with color television have shown that the human psychovisual system is rather insensitive to high frequency components in the directions of I and Q signals. Subjectively acceptable color quality is obtained by reducing the bandwidth of I and Q signals to 1.5 MHz and 0.5 MHz, respectively. In the NTSC system, the composite signal is limited to 4.2 MHz, the I and Q signals to 1.5 and 0.5 MHz, respectively.

The luminance-to-chrominance interference is reduced by choosing the subcarrier frequency  $f_{sc}$  to be an odd multiple of half the line frequency  $f_e$  ( $f_{sc} = 455 f_e/2$ ). This causes the spectral components of these two signals to be interleaved or equivalently changes the phase of the color subcarrier by 180 degrees from line to line. It is this spectral interleaving that permits separation of the chrominance and luminance information using comb filters.

### 2.2.1 European Color TV Systems

European television systems use a different set of transmission tristimulus variables. These variables, denoted by Y,  $C_1$ , and  $C_2$ , are related to the R, G, B, signal as follows:

$$\begin{aligned} Y &= 0.30 R + 0.11 B + 0.59 G \\ C_1 &= R-Y \\ C_2 &= B-Y \end{aligned} \quad (2.4)$$

Comparison of (2.1) and (2.2) with (2.4) shows that both systems utilize the same illuminance components. The difference between the two systems is that both the  $C_1$ ,

$C_2$  components have the same bandwidth and possess the same amounts of energy where in the other system, the bandwidth and energy content of the Q component is less than it is for the I component. Since this transformation is also reversible, one can generate the R, G, B components from Y,  $C_1$ , and  $C_2$  in the ground station to make the system compactable with the NTSC commercial TV system in the United States.

### 2.2.2 Demodulation of Color Signals

Bandwidth compression of television signals exploits the correlation of the signal in both the spatial and temporal directions. To bring out this correlation, the composite color signal must be first demodulated. The field-sequential color signal is already in demodulated form. Spectral correlation of the field-sequential signal can be utilized by simply digitizing two consecutive fields (i.e., corresponding to red and green components) and storing these in digital buffers. The Y, I, and Q components (for each picture element) are then obtained by forming a linear combination of the red and green components with the incoming (blue) component. Demodulation of the NTSC color signal is more complicated. Two popular approaches to this problem are digital color demodulation using comb filters and NTSC to time domain multiplexed (TDM) conversion. However, in a special purpose application such as Shuttle Television where a separate effort is underway to design a NTSC color system for possible use in later missions, one can make small modifications in the camera system to obtain red, blue, and green signals from the camera directly. These signals are then digitized and appropriate conversions to illuminance and tri-stimulus values are made by digital processing.

### 2.3 SLOW-SCAN UPLINK SYSTEM

In addition to down-link transmission of television signals, there exist requirements for transmission of high resolution slow scan black and white pictorial information from the ground station to the Shuttle. The capability of the uplink channel is 144K bits per second and at present, 4 possible modes of operation for the slow-scan uplink system are under considerations. The spatial and gray-level resolution for each mode along with the time which is required to transmit an 8"x10" document is discussed in Section 4.1.2. To maintain the high fidelity of the documents that must be transmitted over the uplink system, one requires bandwidth compression techniques which are entirely distortion-free or introduce minimal distortion. In this study, we consider only distortion-free bandwidth compression techniques for the uplink system.

### 3. A SURVEY OF DIGITAL IMAGE BANDWIDTH COMPRESSION TECHNIQUES

Digital television transmission was first demonstrated nearly 25 years ago by the experiments of Goodall<sup>(2)</sup> with pulse code modulation (PCM). Since then there has been considerable progress in the development of PCM image coding systems<sup>(3-5)</sup>. Their application has been limited, however, because of the extremely high bit rate required for good fidelity transmission. In conventional PCM image coding, for example, a continuous image frame is sampled in the spatial domain to produce an  $M \times N$  array of discrete samples that are then quantized in intensity with  $2^K$  levels where  $K$  is an integer. Then, the total number of bits per second to be transmitted is given by

$$B = MNKF \quad (3.1)$$

where  $F$  denotes the number of frames per second. In the Shuttle television system, an image is scanned with about 350 lines with a horizontal resolution of 425 samples per line at a frame rate of  $F = 60$  frames/sec. If the intensity is quantized to 64 ( $K = 6$ ) levels, this corresponds to a bit rate requirement of 54 Mbps for a non-interlaced color signal that uses a field sequential color camera.

As a result of the wide bandwidth required for conventional PCM television coding, a variety of methods have been explored to reduce the statistical and psychophysical redundancies within an image<sup>(6-10)</sup>. Several of the most promising techniques are listed in Table 3-1. These methods have been classified as to whether the processing is within a frame (intraframe) or between frames (interframe). Furthermore, the methods are categorized as a reduction if achieved simply by deleting image data, while with image compression methods, an attempt is made to exploit the brightness distribution or the spatial and temporal correlation of an image source.

Table 3-1. Image Bandwidth Reduction and Compression Techniques

<u>Intraframe reduction</u>	<u>Intraframe compression</u>
Reduced resolution	Quantization error reduction
Variable spatial resolution	Statistical coding
	Interpolative coding
<u>Interframe reduction</u>	Predictive coding
Reduced frame rate	Transform coding
Picture interlace	
	<u>Interframe compression</u>
	Frame replenishment
	Predictive coding
	Transform coding

The simplest means of intraframe reduction for Shuttle imagery is to limit spatial resolution up to the point that an acceptable picture is obtained. The lower limit of spatial resolution can only be verified by subjective tests. Another approach to intraframe reduction that has been suggested is to position the camera so that an object of interest lies at the center of the frame. Then, since the spatial resolution of a human observer is reduced at the periphery of his field of view, the spatial resolution can be degraded at the periphery of the image. With this system, it is also necessary to constrain the viewer's viewing distance for best results.

Interframe reduction can be accomplished by reducing the frame rate below the 60 frames/sec provided that some form of frame repetition is employed to prevent display flicker. The frame rate lower limit will then depend upon the relative speed of subject movement and the amount of smearing that one is willing to tolerate. Another approach is to employ some form of line or dot interlace in which only a fraction of the pixels of a field are transmitted in a single television field.

Some subjective tests have been made to determine the tradeoff between spatial resolution, frame rate, and brightness quantization<sup>(11)</sup>. Such testing, however, has not been extensive and has not included the field sequential color imagery that Shuttle uses.

When the number of quantization bits is reduced below five, a grey scale contouring degradation usually becomes apparent with standard PCM coding. Preemphasis and deemphasis networks have been employed to reduce quantization error<sup>(2)</sup>. Other approaches include the addition of pseudorandom noise to the video signal before quantization<sup>(13)</sup> and nonlinear quantization<sup>(14,15)</sup>. Also, techniques have been proposed for shaping the quantizing error spectrum by using feedback around the quantizer<sup>(16,17)</sup>. With the best of these techniques, image coding still requires at least 3 bits/pixel.

Statistical measurements on images indicate that the brightness of pixels within a cluster is highly correlated. Entropy calculations of information theory further indicate that statistical coding can be performed on relatively small pixel clusters at an average coding rate of about 1 bit per pixel or less without any loss of information. Unfortunately, there are no known practical implementations of such a coder at realtime television rates.

In interpolative image coding, an image scan line is approximated by simple mathematical functions such as straight line segments to within some error tolerance<sup>(7)</sup>. The method results in excellent fidelity at a coding rate down to 1 bit/pixel. Unfortunately, the interpolation algorithms are complex and completely unsuitable to realtime television implementation.

The intraframe and interframe coding techniques which use predictive coding and transform coding methods have proven to be practical for television bandwidth reduction. These methods are described in greater detail in the following sections along with a hybrid transform/predictive coding method.

### 3.1 INTRAFRAME CODING OF PICTORIAL DATA

In intraframe coding of pictorial data, the spatial correlation of picture elements is utilized to generate a set of uncorrelated or nearly uncorrelated signals from the pictorial data. The bandwidth reduction is then achieved by not transmitting a fraction of the uncorrelated signals or quantizing them very coarsely. The intraframe coding techniques ignore the temporal correlation and thus are not as efficient as their equivalent interframe coding methods. In general, however, they are less complicated than the corresponding interframe encoders.

#### 3.1.1 Transform Image Coding

Even though fine sampling and quantization of an image are essential for desirable subjective quality of a digital picture, from the viewpoint of a statistician, the information in the picture can be conveyed quite adequately without all these variables. On the otherhand one cannot simply discard a part of these because of their equal statistical significance and the adverse effect that this would have on the subjective quality of the picture.

An approach to this problem is to transform the image samples to a new set of variates that have a complementary degree of significance in contributing to both the information content and the subjective quality of the resulting picture. Then one can discard the less significant of these variables without affecting the statistical information content of the picture or causing a severe degradation in the subjective quality of the picture. The method of "principal components" (better known as the discrete Karhunen-Loeve transformation) is a linear transformation with the above properties<sup>(18,19)</sup>. A number of other unitary transformations such as Hadamard, Fourier, Haar, Slant, and Cosine transforms also possess this property to some extent.

As indicated in Figure 3-1, these transform coding algorithms perform a unitary transformation on the input data and follow this by some form of quantization in the

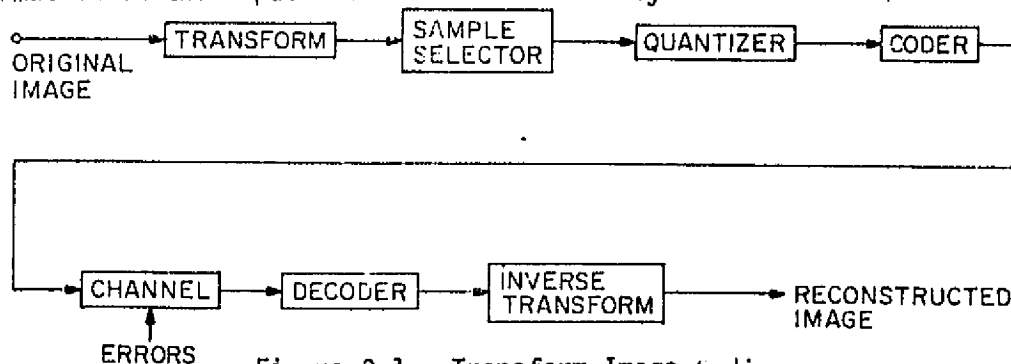


Figure 3-1. Transform Image Coding

transform domain. At the receiver, the inverse transform is performed on the quantized values to restore the original data within some level of degradation. Theoretical and experimental results indicate that the transformed samples can be well modeled by a Gaussian distribution and are best quantized by a nonlinear quantizer. The forward and inverse two-dimensional Karhunen-Loeve transformations are given by

$$u_{ij} = \sum_{y=1}^N \sum_{x=1}^N \phi_{ij}(x,y) u(x,y) \quad (3.2)$$

$$u(x,y) = \sum_{i=1}^N \sum_{j=1}^N \phi_{ij}(x,y) u_{ij} \quad (3.3)$$

It has been shown that the "eigenmatrices" (2) of  $\phi_{ij}(x,y)$  of the whole picture or subblocks of the picture that are composed of  $N$  by  $N$  pixels can be formed from outer products of eigenvectors of the covariance of the data in the horizontal and the vertical directions if the covariance of the data is separable and of the form

$$R(x,y,\hat{x},\hat{y}) = R_H(x,\hat{x}) R_V(y,\hat{y}) \quad (3.4)$$

where  $R_H$  and  $R_V$  refer to the covariance matrices of the data in horizontal and vertical directions, and  $R(x,\hat{x},y,\hat{y})$  is the covariance "tensor" of the data. In the absence of this assumption, the ordering of the two-dimensional data in a vector form is the only practical solution. Computations indicated by equations (3.2) and (3.3) correspond to operating on the rows of the image followed by operations on the columns of the horizontally transformed data to obtain the two-dimensional transformation. Approximately  $N^4$  multiplication/addition operations are required to perform the transformation. Often the two-dimensional Karhunen-Loeve transformation is obtained for the Markov process covariance function

$$R(x,\hat{x},y,\hat{y}) = \exp(-\alpha|x-\hat{x}| - \beta|y-\hat{y}|) \quad (3.5)$$

where  $\alpha$  and  $\beta$  are estimated from the image.

The shortcomings of the method of principal components are the large number of operations required for forward and inverse transformation of (3.2) and (3.3), estimation of the covariance of the data, and calculation of the eigenmatrices. To eliminate these difficulties, a number of other transformations have been considered and are reviewed briefly below (see References 20 to 27 for details).

For discrete data, the two-dimensional Fourier transformation corresponds to choosing the basis matrices (images) of the form

$$\phi_{ij}(x,y) = \left\{ \frac{1}{N} \exp \left[ \frac{-2\pi(-1)^{1/2}}{N} (ix+jy) \right] \right\} \quad (3.6)$$

$$i,j,x,y = 1,2,\dots,N$$

while the two-dimensional Hadamard transform<sup>(20,23)</sup> corresponds to choosing basis images as

$$\phi_{ij}(x,y) = \frac{1}{N} (-1)^{\left\{ \sum_{h=0}^{\log_2 N - 1} [b_h(x)b_h(y) + b_h(i)b_h(j)] \right\}} \quad (3.7)$$

where  $b_h(\cdot)$  is the  $h^{\text{th}}$  bit in the binary representation of  $(\cdot)$ , and  $N$  is a power of 2. Both of the above transformations are members of a class of Kronecker matrix transformations that have  $2N^2 \log_2 N^2$  degrees of freedom, and can therefore be implemented by  $2N^2 \log_2 N^2$  computer operations. These transformations remedy the shortcomings of the Karhunen-Loeve transformation by eliminating the necessity of finding an operator matched to the covariance of the image and significantly reducing the computational complexity.

In addition to these transformations, a number of others possessing the above two properties have been considered. For example, Cosine<sup>(26)</sup> and Slant transformations<sup>(27,28)</sup> have resulted in a better mean square error performance than either the Fourier or the Hadamard transformations. The performance of these transforms is still inferior to the performance of the Karhunen-Loeve transformation, which is the only orthogonal transform that generates a set of uncorrelated signals. However, in most practical applications, the computational simplicity and the ease of implementation of the Hadamard and other suboptimum transformations more than compensates for the suboptimal performance of the transforms.

Relatively simple transform image coding algorithms have been developed which yield good fidelity results for coding with about 1 to 2 bits/pixel in relatively small size blocks. The disadvantages of transform coding are primarily implementation complexity. With most hardware implementation methods it is necessary to store a number of television lines equal to the block size, e.g., 16 lines for a 16 x 16 block. Also, for realtime TV systems, if implementation is to be performed with digital circuitry, a relatively large number of high speed adders, multipliers, and storage registers will be required even with a fast computational algorithm.

### 3.1.2 Predictive Image Coding

Conventional PCM is a relatively inefficient form of coding for images, since the process ignores the spatial correlation of pixels. Transform coding, on the other hand, exploits the spatial correlation by transforming pixel regions to a set of transform coefficients which are nearly uncorrelated and can be efficiently coded separately with a relatively small number of bits.

Another means of de-correlation of an image is based on classical prediction theory. Consider the linear predictive coder of Figure 3-2, in which a set of correlated variables  $[S_i]$  with mean zero and variance  $\sigma^2$  is to be coded. A linear predictor provides an estimate of the next sample  $S_0$  by  $\hat{S}_0$  based on the previous  $n$  samples by the linear operation

$$S_0 = \sum_{i=1}^n A_i S_i \quad (3.8)$$

Next, a differential signal

$$e_0 = S_0 - \hat{S}_0 \quad (3.9)$$

is formed. In a predictive coding system, the differential signal is quantized and coded. At the receiver, the reconstructed differential signal is used to recreate the sample estimate  $\hat{S}_0$ . The weighting coefficients  $A_i$  are chosen to minimize the variance of the differential signal for efficient quantization and coding. Experimental results for images indicate that use of only the three nearest neighbors of a pixel results in a nearly uncorrelated set of differential signals for transmission.

The linear predictive coder, often called a differential PCM coder, forms its prediction based on observations in two dimensions. Often such coders are restricted to prediction only along a scan line to simplify implementation. Such designs, however, result in degraded performance<sup>(29,31)</sup>.

The delta modulator is a simplified form of a DPCM coder in which the prediction is based only on the previous pixel, and the differential signal is quantized only to two levels. Such gross quantization usually results in severe distortion. Adaptive delta modulation schemes have been developed to adjust the quantization levels to image brightness changes. Also, a dual mode DPCM/delta modulation coder has been developed in which the coder operates in a delta modulation state in image regions of nearly constant brightness and switches to DPCM in regions of rapid brightness changes<sup>(32)</sup>.

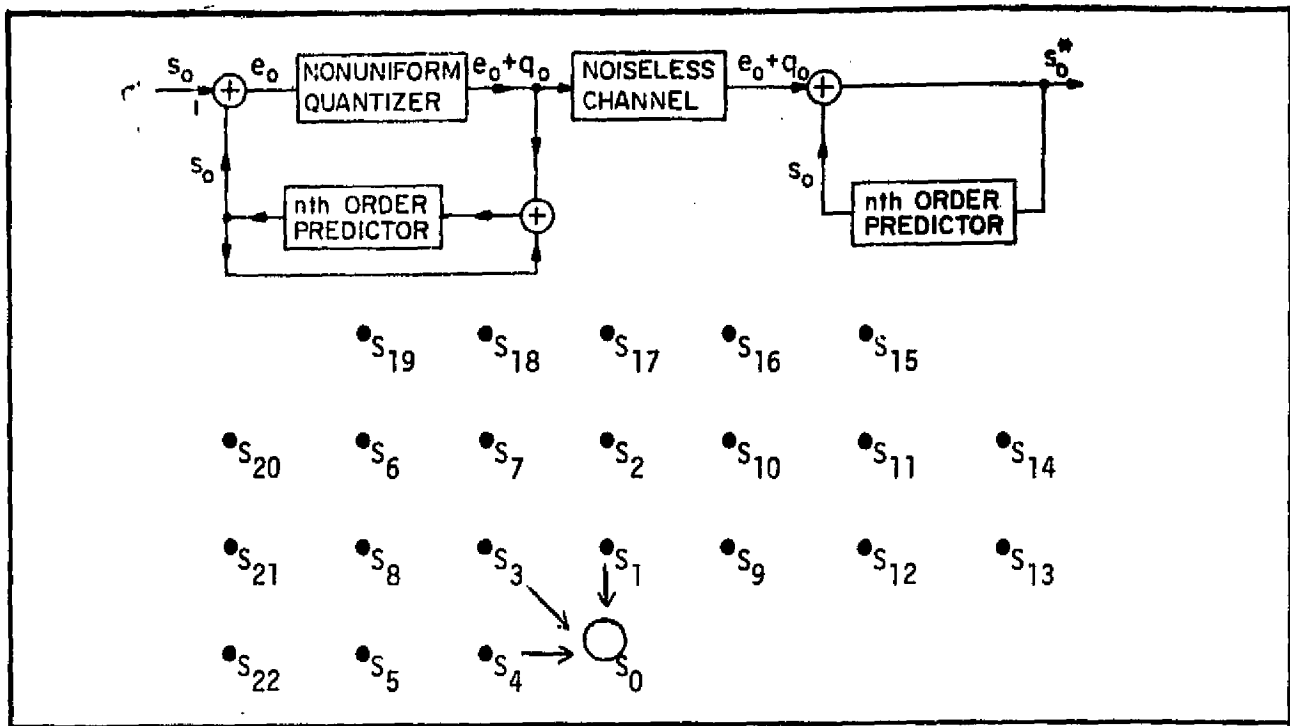


Figure 3-2. Linear Predictive Coder and the Pixels Employed in Predicting Pixel  $S_0$

Spatial domain predictive coders have proven to provide relatively good fidelity for coding with as few as 2 bits/pixel. Furthermore, the implementation complexity of such coders is reasonable for realtime television at resolutions of commercial quality.

### 3.1.2.1 DPCM Systems with Adaptive Predictors

DPCM systems using a fixed optimized predictor generate a well behaved stationary differential signal if the original data is stationary. The stationary differential signal can be encoded optimally using a nonlinear quantizer matched to its statistics. However, when the signal is non-stationary and the predictor parameters are fixed, a non-stationary differential signal results. Optimal encoding of the non-stationary differential signal then requires a variable quantizer which would change to accommodate the variations in the differential signal. In designing an adaptive DPCM system one must either use a predictor with variable parameters such that the parameters would change with the variations in the signal (always generating a stationary differential signal) or one can use a fixed predictor with a variable quantizer to accommodate the resultant non-stationary differential signal. In addition to the above two adaptive systems, the adaptivity can be incorporated in the system by using a variable sampling rate and fixing both the predictor and the quantizer.

In a DPCM system with an adaptive linear predictor, the weightings on the adjacent samples used in predicting an incoming sample can change according to variations in

the signal value. Atal and Schroeder<sup>(28)</sup> studied the performance of such an adaptive system for voice signals. Their proposed system included a 5 millisecond delay during which the incoming samples were stored in an input buffer and were used to obtain an estimate of signal covariance matrix. The measured covariance matrix was used to obtain a set of weightings for the predictor. These values were then used for processing the stored signals. The updated values of the predictor coefficients need to be transmitted to the receiver once every 5 milliseconds. They used the variable predictor with a two level quantizer and report good coding results. Although identical systems can be implemented for coding pictorial data, this type of system has not been reported in open literature. Instead, researchers have used adaptive DPCM systems with a fixed and simple predictor and an adaptive quantizer.

### 3.1.2.2 DPCM Systems with Adaptive Quantizers

A DPCM system with a fixed predictor will have a non-stationary differential signal for non-stationary data. Using a fixed quantizer, non-stationary differential signals would cause an abnormal saturation or a frequent utilization of the smallest level in the quantizer. To remedy this situation the threshold and the reconstruction levels of the quantizer must be made variable to expand and contract according to signal statistics. Adaption of the quantizer to signal statistics is accomplished using various approaches. Virupaksha and O'Neal<sup>(29)</sup> suggested an adaptive DPCM system for speech signal that stores 25 samples of the differential signal to obtain an estimate for the local standard deviation of the signal. Then the stored signal is normalized by the estimated standard deviation and is quantized using a fixed quantizer. Naturally the scaling coefficient must be transmitted once for every 25 samples for receiver synchronization. Ready and Spencer<sup>(30)</sup> use a similar approach in a system called Block-Adaptive DPCM that they use for bandwidth compression of monochrome images. In Block-Adaptive DPCM Systems a block of  $M$  samples is stored and is normalized by  $n$  possible constants. The total distortion for all  $M$  samples using each normalizing constant is calculated at the encoder. The normalizing constant giving the smallest distortion is used to scale the samples in the block prior to their quantization and transmission. The system requires  $(\log_2 n)/M$  binary digits per sample overhead information for receiver synchronization. Ready and Spencer use a two dimensional DPCM system employing 3 adjacent samples in its predictor and use a block of 16 samples with 4 possible normalizing constants. They report a 36% reduction in bit rate over a similar non-adaptive DPCM system at about 2 bits per sample. The improvement in performance is less at higher bit rates.

A different approach, which has not appeared in technical literature, is a DPCM system with a variable set of thresholds and reconstruction levels. This is the self synchronizing approach used in adaptive delta modulators where the step size contracts and expands depending upon the polarity of sequential output levels. In a DPCM quan-

tizer the set of threshold and reconstruction levels would contract and expand depending upon the sequential utilization of inner or outer levels of the quantizer. For instance, a variable quantizer can be designed where all reconstruction levels expand by a factor of  $P$  (for some optimum value of  $P$ ) upon two sequential happenings of the outermost level and they would contract by a factor of  $\frac{1}{P}$  upon two sequential happenings of the smallest level. This system has the advantage that it is completely adaptive and does not require any overhead information because the receiver is self synchronizing.

### 3.1.3 Hybrid Transform/DPCM Image Coding

Analysis of the transform and DPCM image coding techniques has disclosed that each possesses attractive characteristics and some limitations<sup>(33,34)</sup>. Transform coding systems achieve superior coding performance at lower bit rates; they distribute coding degradation in a manner less objectionable to a human viewer, show less sensitivity to data statistics (picture-to-picture variation), and are less vulnerable to channel noise. DPCM systems, on the other hand, when designed to take advantage of spatial correlation of image data, achieve a better coding performance at a higher bit rate. Perhaps the most desirable characteristic of DPCM is the ease of design and the speed of the operation that has made it possible for DPCM systems to be used in coding television signals in real time. The limitations of DPCM are the sensitivity of even well-designed systems to picture statistics and the propagation of channel errors in a coded picture.

A hybrid coding system that combines the attractive features of both transform and DPCM coding has been developed<sup>(34)</sup>. This system exploits the correlation of the data in the horizontal direction by taking a one-dimensional transform of each line of the picture, then operating on each column of the transformed data using a one-element predictor DPCM system. Since the unitary transformation involved is a one-dimensional transformation of individual lines of the pictorial data, the equipment complexity and the number of computational operations are considerably less than that involved in a two-dimensional transformation. Theoretical and experimental results indicate that the hybrid system has good coding capability — one that surpasses both DPCM and the transform coding systems.

In the hybrid system shown in Figure 3-3, image data is scanned to form  $N$  lines, and each line is sampled at the Nyquist rate. This sampled image is then divided into arrays of  $N$  by  $M$  picture elements  $u(x,y)$ , where  $x$  and  $y$  index the rows and the columns in each individual array, so that the number of samples in a line is

an integer multiple of M. The one-dimensional unitary transformation of the data and its inverse are modeled by the set of equations

$$u_i(y) = \sum_{x=1}^M u(x,y) \phi_i(x) \quad \begin{matrix} i = 1, 2, \dots, M \\ y = 1, 2, \dots, N \end{matrix} \quad (10a)$$

$$u(x,y) = \sum_{i=1}^M u_i(y) \phi_i(x) \quad (10b)$$

where  $\phi_i(x)$  denotes a set of M orthonormal basis vectors. Since the correlation of samples in various columns of the transformed array is different, a separate DPCM loop is used to encode each transform coefficient.

The performance of three hybrid encoders using various transformations is shown in Figure 3-4 for M=16 and N=256. The performance of the two-dimensional Hadamard and two-dimensional DPCM encoders is included for comparison. This figure clearly shows the superior performance of the hybrid encoder over both the two-dimensional Hadamard and two-dimensional DPCM encoders.

The optimal hybrid coder (Figure 3-3) utilizes a set of different weighting coefficients  $A_1, A_2, \dots, A_M$  in the DPCM predictors at the transmitter and receiver. Also, the quantizers in the DPCM systems are based on the statistics of the video data. To simplify the encoder and permit its design to be independent of the signal statistics, a suboptimal system has been developed which uses a common value for  $A_1$  through  $A_M$ , and which uses some general statistics (obtained from a number of typical pictures) to obtain variances of the transform coefficient. In the block diagram of the simplified DPCM encoder (Figure 3-5), a single loop encodes all transform coefficients in a sequential manner. Each transform coefficient is normalized by multiplying by an appropriate gain factor  $g_i$  before being processed by the DPCM loop. The processed system has a maximum of 4 bits per coefficient. The bit assignment procedure is programmed in the controller which selects 0 to 4 bits per coefficient in a predetermined manner. The nonlinearity of the quantizer is achieved by using a set of fixed non-uniform threshold levels.

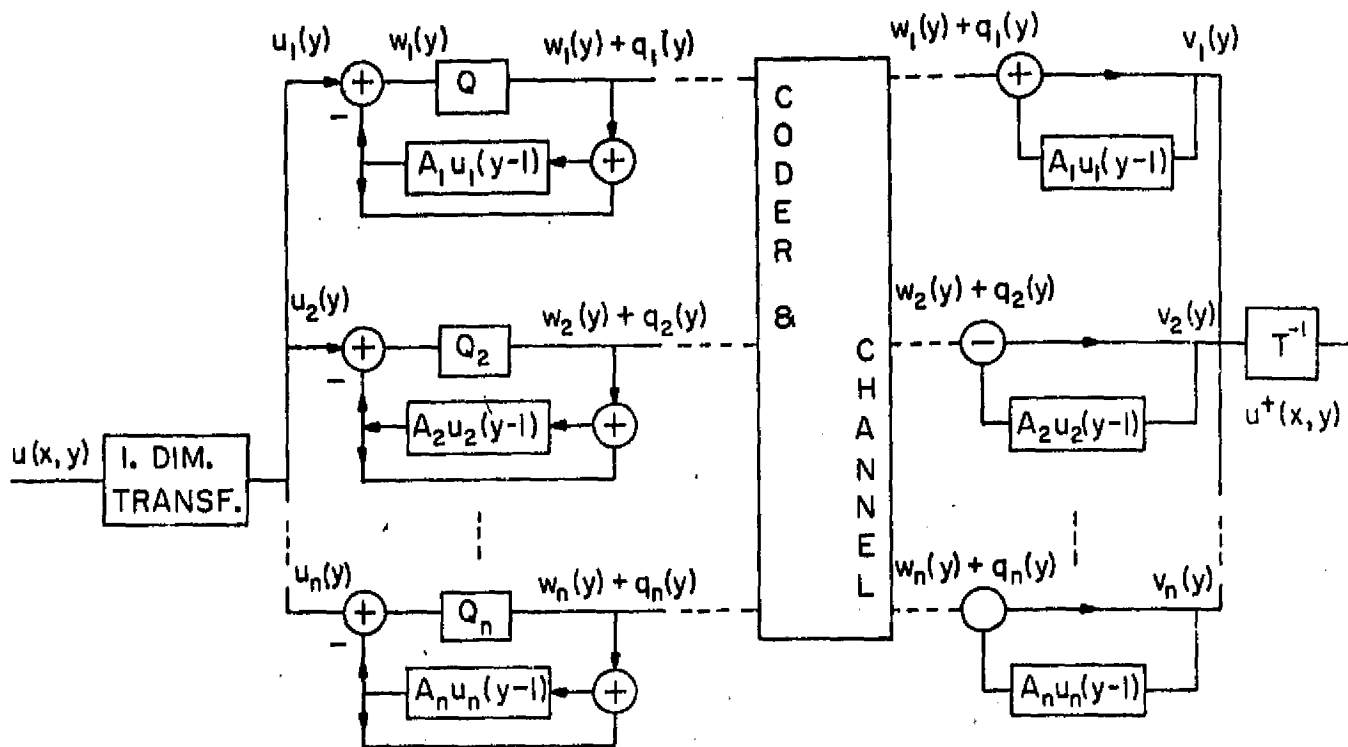


Figure 3-3. Hybrid Transform/DPCM Image Coder

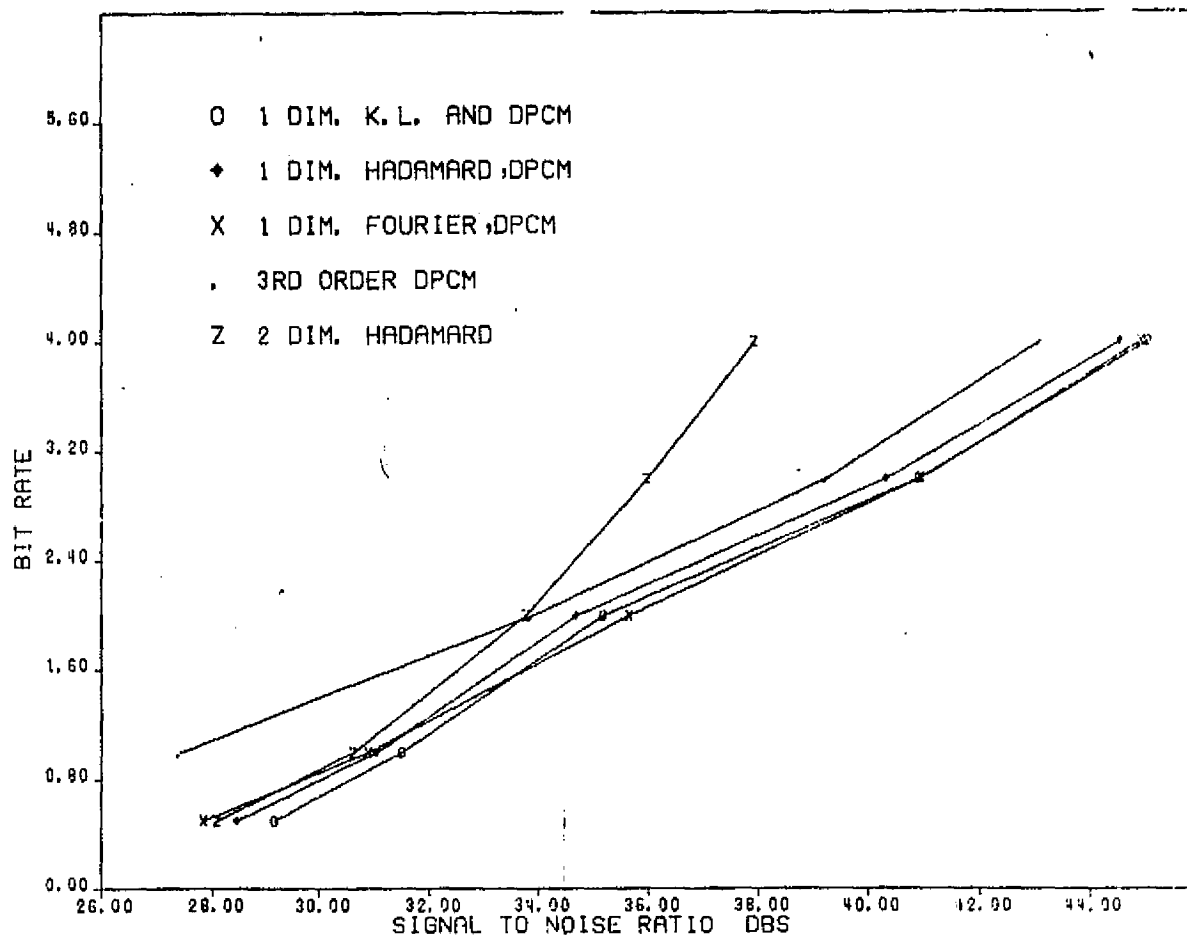


Figure 3-4. Experimental Results Comparing the Performance of the Proposed Hybrid Systems Using a Typical Video Scene. The performance of a third-order simple DPCM and the encoder using a two-dimensional Hadamard transform and a block quantizer is included for comparison.

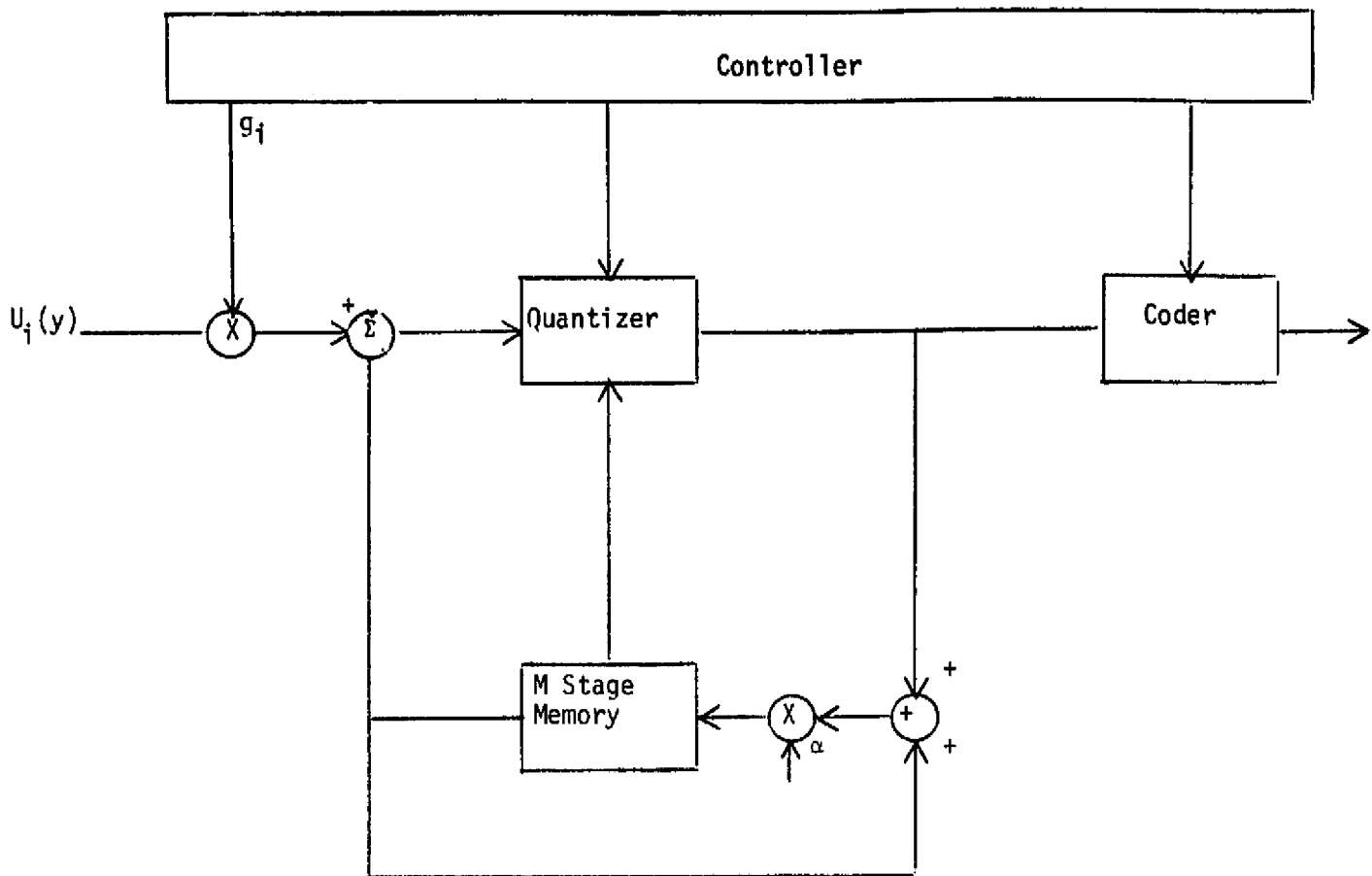


Figure 3-5. DPCM Encoders for the Simplified Hybrid Encoder

The simulation results show that performance of the simplified hybrid encoder is only slightly inferior to the performance of the optimum hybrid encoder. The reduction in SNR and subjective quality was minimal and well worth the resulting hardware simplification.

### 3.2 INTERFRAME CODING OF TELEVISION SIGNALS

In a monochrome television signal, a large fraction of the picture elements correspond to background material that does not change significantly from one frame to the next, while only a relatively small number of picture elements in a frame convey fresh information. From a statistical viewpoint, the similarity of pixels from one frame to the next corresponds to a high level of interframe correlation. Thus, the statistical coding techniques exploiting spatial correlation that have been considered for coding single frames of data could, in principle, be extended to take advantage of the frame-to-frame correlation, thereby further reducing the bit rate required to transmit the data. Indeed, some research in the area of three-dimensional Fourier and Hadamard transformations has indicated that bit rates can be reduced by a factor of about 5 by incorporating the correlation in the temporal direction<sup>(35)</sup>. However, three-dimensional transform encoding systems suffer from the serious shortcomings of computational complexity and the requirement of large amounts of storage. For this reason, some

researchers have avoided extending transform coding systems to a third dimension; instead they have suggested suboptimum coding systems that do not require extensive amounts of memory or computation.

Interframe coding of frame-sequential color signals of Space Shuttle suffer from an additional shortcoming. This is due to the fact that, in frame-sequential color television, the sequential frames represent both motion and spectral changes, whereas in monochrome television sequential frames differ only due to the motion of the camera with respect to the subject. This limits the coding efficiency of the interframe coding systems since spectral variations, as encountered in going from a blue to a red component of a color signal, are more significant than changes due to motion of the camera with respect to the subject. Efficient coding of the frame-sequential color television signal requires using the sequential color signals to generate the illuminance and chromaticity components of the color video signals on-board the spacecraft and then applying the interframe coding to the illuminance and chromaticity components individually. Naturally, this involves preprocessing the data on-board the spacecraft and requires storing three frames to make the required transformation. Interframe coding of the new color composite signals may require additional frame storage. This approach may not be feasible due to the light weight and the low power requirements for the on-board encoder.

Other approaches include application of only intraframe coding methods or using interframe coding algorithms on the frame-sequential color data directly. Using the second approach, one would want to use a coding algorithm that would make maximum use of the similarities of frame-sequential color signals. In the following, we discuss a number of interframe coding algorithms which have been devised for coding monochrome television signals. We address the anticipated performance of these systems for the frame-sequential color video signal.

### 3.2.1 Conditional Frame Replenishment Coding

An efficient technique of interframe coding of monochrome television images is simply to transmit the gray levels of the elements that have changed in successive frames by replenishing the previous frames with the transmitted data<sup>(36,37)</sup>. Experiments with Picturephone signals using the conditional frame replenishment technique have indicated good coding results for an average of 1 bit per pixel. A major shortcoming of the system is that the data is generated at an uneven rate. This is caused by the variation in number of pixels which change beyond a fixed threshold in each frame. To transmit this data over a fixed bit rate channel requires buffering the data prior to transmission. The size of the buffer and the bit rate limit the amount of motion in the video data for which this system can be employed. It has been determined that a buffer size of 10 frames is needed to transmit television signals with a moderate degree of motion. The buffer size can be reduced to one frame by transmitting only clusters of data at the expense of increased hardware complexity.

A second major shortcoming of the system is that only correlation of the data in the temporal direction is exploited. Thus, the overall efficiency of the coder is low, since spatial correlations are ignored. This coding system can be modified to encode illuminance and the chromaticity components individually. Hardware development of such an encoder is under study in Japan. The performance of the frame replenishment algorithm on frame-sequential color signals is anticipated to be rather poor, since there is a considerable change in the background caused by spectral variation.

### 3.2.2 Three-Dimensional Hadamard Transform Coding

A three-dimensional coding system that takes a transformation in the temporal direction as well as the spatial domain exploits the frame-to-frame correlation as well as the correlation in the temporal direction, thus achieving a better coding performance than the two-dimensional transform coding methods. Although it is possible to use any of the unitary transformations, the complexity of the system is reduced by using a Hadamard transform that requires minimal hardware complexity. At least two coding methods using three-dimensional Hadamard transformation are under development in the United States.

#### BTL Three-Dimensional Hadamard Transform Coding System

A three-dimensional Hadamard coder which employs  $2 \times 2$  pixel blocks by 2 frames in time is currently under investigation at Bell Telephone Laboratories. This system exploits the correlation of data in both the spatial and temporal directions, requires only one frame of memory, and is amenable to simple hardware implementation. However, this coding technique is not highly efficient due to the rather small number of pixels (a total of eight pixels) used to exploit correlations in the data. Hardware for this encoder is in the development stage at Bell Telephone Laboratory<sup>(38)</sup>.

#### NASA/Ames Three-Dimensional Hadamard Transform Coding System

NASA/Ames Research Center at Moffit Field, California, has developed a three-dimensional Hadamard transform coder that uses a block size of  $4 \times 4$  pixels and four frames in time. This coder is designed to reduce the bandwidth of high resolution television signals transmitted at 30 fps. It employs a  $4 \times 4$  pixel sliding window technique to eliminate visual edge effects due to the Hadamard encoder.

The encoder is designed for standard U.S. commercial television signals and thus uses 525 lines per frame. Each line is sampled to generate 512 samples per line. This corresponds to 8 megasamples per second on a corresponding 4 MHz analog bandwidth for the original television signal. A functional block diagram of this encoder is shown in Figure 3-6. The Hadamard transformation is applied to subblocks of  $4 \times 4 \times 4$  samples. The bandwidth reduction is obtained by assigning more bits to lower coefficients and less bits to higher coefficients. The system is capable of

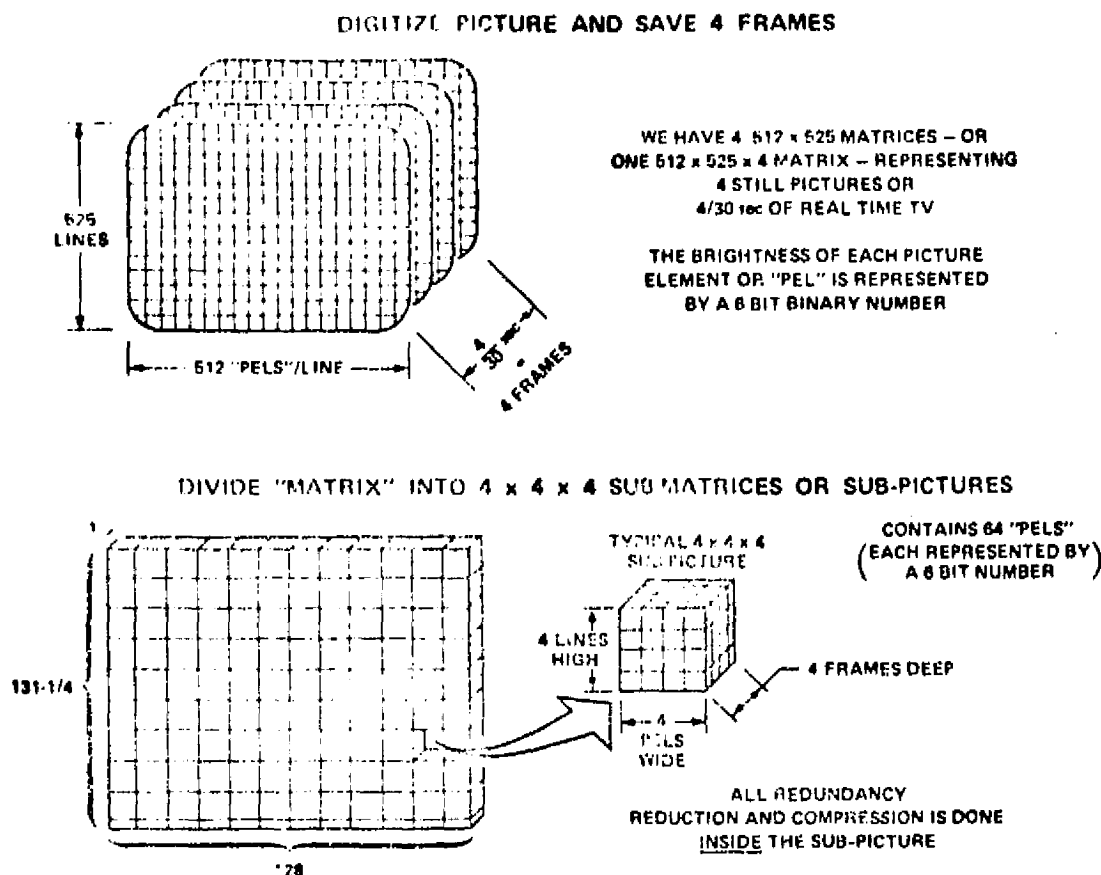


Figure 3-6. 3D Hadamard Encoder

operating from off-the-air television signal, video tapes, or television cameras. A block diagram showing the field demultiplexing essential to perform the three-dimensional Hadamard transform of interlaced signals is shown in Figure 3-7. A block diagram of the decoder is shown in Figure 3-8. The system can be programmed to operate at various bit rates. It also has an adaptive mode of operation that selects a combination of vectors and cut points best fitted to the data.

The shortcoming of this system is the large storage requirements needed for four frames of data. The system can be modified to encode color television by operating on the illuminance and the chromaticity components individually. This requires storing as many as 12 frames of data at the transmitter, though it is conceivable that this number could be reduced due to the fact that the chromaticity signals require a much smaller bandwidth. The performance of the existing encoder operating on a frame-sequential color video signal is anticipated to be inferior to its performance on monochrome television due to smaller correlation in the spectral bands as compared to the correlation of sequential frames in monochrome video signals.

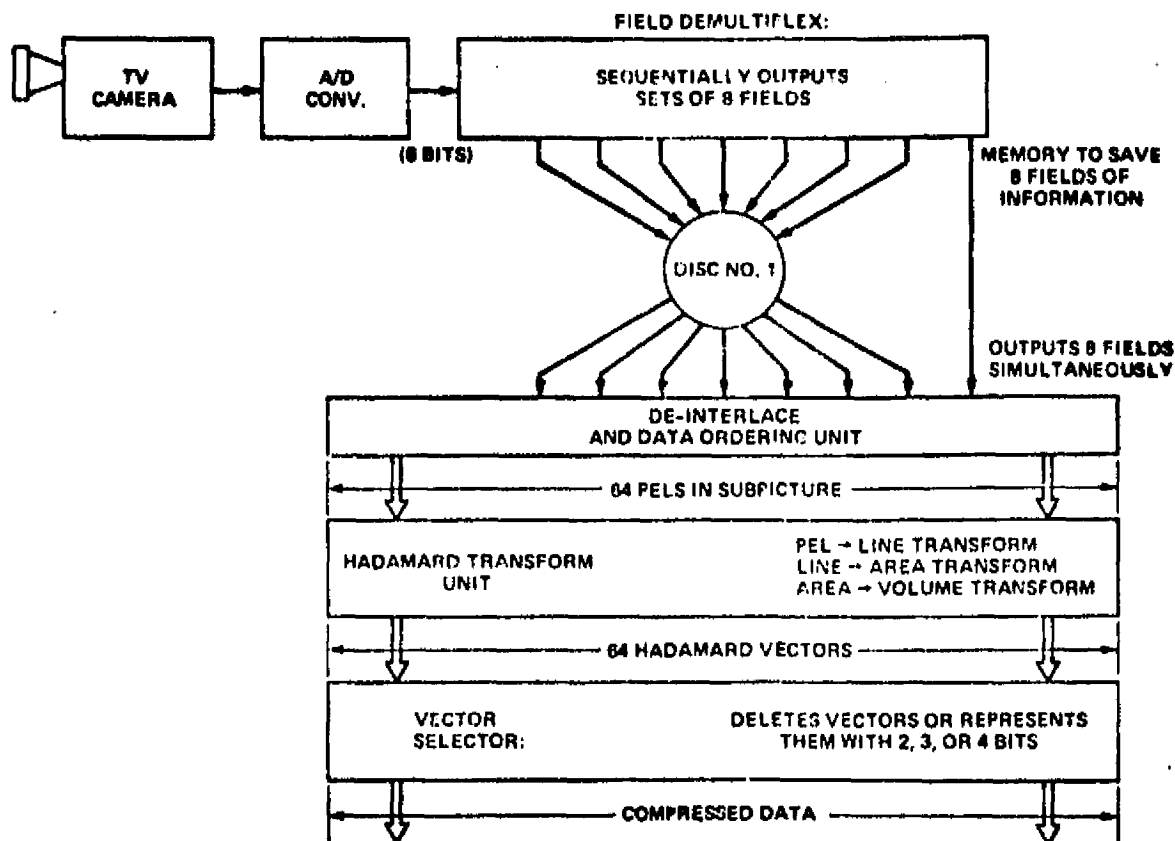


Figure 3-7. Field Demultiplexer  
DECODE SYSTEM

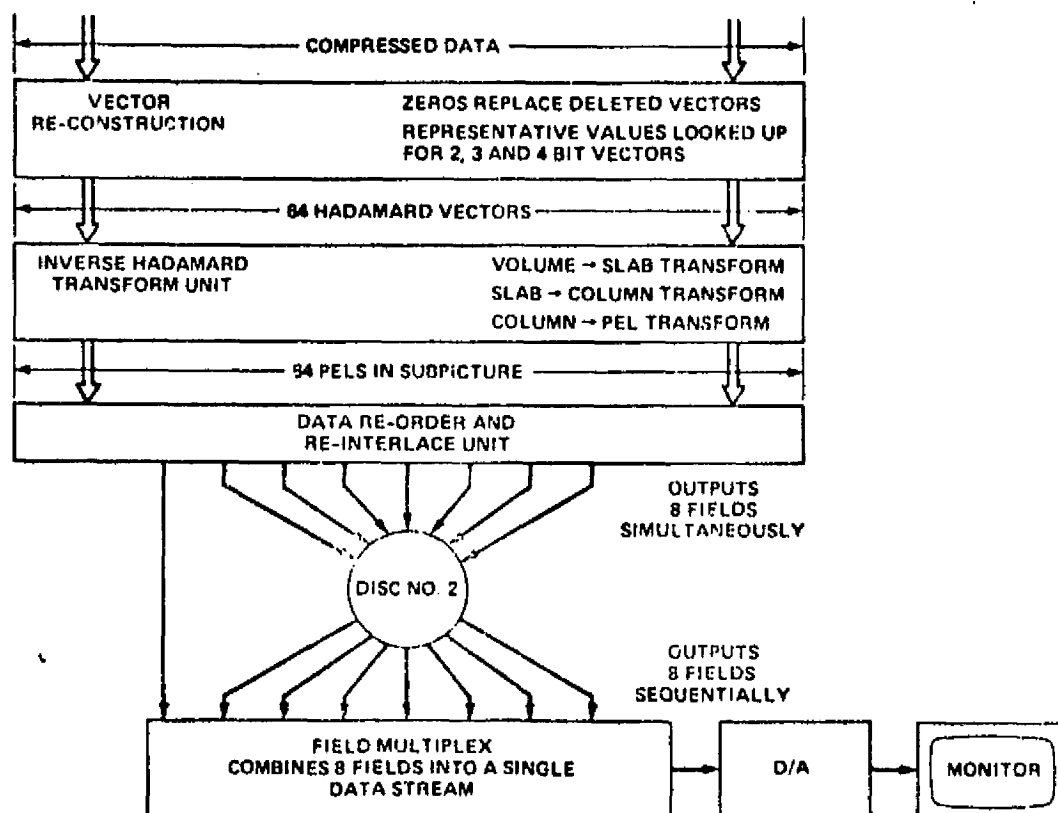


Figure 3-8. Field Multiplexer

### 3.2.3 Three-Dimensional Hybrid Encoders

Three-dimensional transform coding systems suffer from the shortcoming of excessive storage requirements needed to store previous frames. A three-dimensional hybrid encoder that uses a two-dimensional transformation on the spatial domain cascaded with a DPCM encoder in the temporal domain will require storing only one frame of data and should perform better than the corresponding three-dimensional encoders. This observation is based on the comparative performance of the two-dimensional hybrid and transform encoders which were discussed in Section 3.1.1. In the following, we describe three different coding algorithms that are based on three-dimensional hybrid encoders.

#### Two-Dimensional Cosine Transform/DPCM Encoder

Investigation of the hybrid encoder using a two-dimensional cosine transform cascaded with a DPCM encoder for reducing the bandwidth of RPV imagery is underway by the Naval Undersea Center in San Diego<sup>(39)</sup>. This hybrid encoder exploits spatial correlation of a television image by taking a two-dimensional discrete cosine transform. Temporal correlation of the data is exploited by using a DPCM encoder. Theoretical studies indicate that the hybrid interframe encoder possesses the attractive feature of the hybrid intraframe encoder discussed in Section 3.1.1. It is anticipated that this system will reduce the number of binary digits needed for reconstruction of television at the receiver by a factor of about 5 over the two-dimensional hybrid encoder. This system can be modified to encode illuminance and the chromaticity components of a color video signal. This requires storing three frames of data at the transmitter. The performance of this system operating directly on the frame-sequential color video data is expected to be inferior to its performance for monochrome television signals.

#### Two-Dimensional Fourier Transform/DPCM Encoder

An alternative approach to the three-dimensional hybrid encoder that uses the cosine transform in the spatial and the DPCM encoder in the temporal direction is a system using a two-dimensional Fourier transform. This system would generate a two-dimensional Fourier transform of each frame. Denoting the two-dimensional Fourier transform of the  $k^{\text{th}}$  frame by  $F_k(u,v)$ , we can represent  $F_k(u,v)$  by its amplitude and phase as

$$F_k(u,v) = A_k(u,v) e^{j\theta_k(u,v)} \quad (3.11)$$

where  $A_k(u,v)$  and  $\theta_k(u,v)$  refer to the amplitude and phase planes of the  $k^{\text{th}}$  frame. Many types of motion (such as a panned motion) correspond to significant changes in the phase plane and small changes in the amplitude plane. Thus, for an efficient encoder, we would assign a larger fraction of the available binary digits to changes

in the phase plane from one frame to the other frame and a smaller number of binary digits to the corresponding changes from one amplitude frame to the other. The other attractive feature of this coding method is relating the predictor in the DPCM feedback loop to the motion and performing a better prediction for the changes in phase caused by the motion. This system is more complex than the three-dimensional hybrid encoder that uses the cosine transform. The performance of this encoder on the frame-sequential color signal is anticipated to be better than other three-dimensional coding methods, since it is conceivable that spectral variations and motion will be registered sufficiently different in the amplitude and phase planes to allow for more efficient coding of these variations.

#### Two-Dimensional Hadamard/Frame Differencing

The three-dimensional hybrid encoder discussed above uses a two-dimensional transformation on the spatial domain, and then the transform coefficients are encoded by DPCM encoders in the temporal domain. The system can be simplified if only the difference of the transform coefficients is quantized. This corresponds to using a gain of unity in the feedback loop of the DPCM encoder. In the three-dimensional hybrid scheme. Such a system is implemented by Linkabit Corporation using two-dimensional  $4 \times 4$  Hadamard transform<sup>(40)</sup>. The error propagation is reduced by quantizing and sending the transform coefficients once every four frames instead of the frame-difference signals. The performance of this encoder is degraded if frame-sequential color signals are used instead of the sequential frames of monochrome television.

### 3.3 FACSIMILE CODING TECHNIQUES

Transmission of video information over PCM channels requires sampling of the analog signal to form pixels and then quantizing each pixel to one of  $2^M$  levels. Each pixel is then transmitted using M binary digits. Two-level data (also called two-tone) such as weather maps or printed materials require only a single binary digit while continuous grey-tone pictures usually need 6 to 8 binary digits for a satisfactory representation. Since the entropy of both types of data sources is smaller than the number of binary digits M, a redundancy reduction technique will, in most cases, result in a reduction in the bit rate without reducing the information content of the data. Redundancy reduction techniques considered for the two data types are in general different. Continuous grey-tone pictures are characterized by smooth edges and small sample to sample variations and can be encoded by transform techniques (Fourier, Hadamard, Karhunen-Loeve Transform) and some of the predictive coding techniques (DPCM and delta modulators). All these techniques degrade the transmitted picture although in most cases the degradation is virtually unnoticeable when encoded at 1 to 2 binary digits per pixel. The half-tone sources (sometimes referred to as binary sources), on the other hand, are characterized by sharp edges and often require encoding with no degradation. The techniques developed for these sources are, in general, information preserving, such as Huffman coding and are decoded at the receiver to prove an exact replica of the source data. A third type of data source proves multi-level data that is characterized by sharp edges and a limited number of grey levels. An example is a road map or a diagram that uses a few different shades of grey. Due to the limited number of levels and sharp edges that characterize this type of data source, it can be encoded using modified forms of the algorithms that are developed for encoding two-level data. In this section different techniques of encoding two-level sources are reviewed and the potential use of these techniques on multilevel 2-dimensional data is studied.

The techniques developed for encoding binary 2-dimensional data can be classified into two categories. The first is the class of techniques that encodes each scan line of pixels independently. The correlation between picture elements along the line is used to reduce the redundancy inherent in that line. These techniques ignore the correlations between lines. The second class of techniques store a portion of a frame or a complete frame and consider the correlation between the picture elements in more than one direction. Most of these techniques utilize the correlation in the vertical as well as the horizontal direction; others go further and include correlations at all possible angles. Theory and experiments have shown that the second class of techniques produce better reconstructed picture fidelity.

### 3.3.1 One-Dimensional Techniques

The major encoding techniques in the first class are:

1. Run-Length Coding - In this technique a counter keeps track of the number of consecutive similar symbols (0's or 1's). These numbers, which are the length of the run of black or white symbols, are encoded using some entropy coding technique such as a Huffman code. A thorough performance evaluation of this technique in encoding printed materials and weather maps is carried out by Huang<sup>(41)</sup>. In addition to the experimental performance evaluation of run-length coding on 3 weather maps and 4 pages of type written materials of varying resolutions, he has verified an upperbound on the average number of bits/pixel required by the technique. Based upon a two-state Markov chain model Huang finds an upperbound on the run-length coding techniques of any two-level data regardless of its statistics.

Run-length coding technique can be applied to multi-level data where  $m$  additional bits per run are used to specify the value of each run for a data source with  $2^m$  possible levels. Here each run is designated by two numbers, one specifying the length and the other magnitude. Since there is no logical relationship between these two numbers, each can be encoded independently. A Huffman code based on average statistics of the data (histograms of the run lengths and run values over an ensemble of pictures) can be used to encode these numbers into code words.

An optimized form of run-length coding technique is suggested by Bradley for two-level data<sup>(42)</sup>. This coding technique considers each run as a string of "zeros" with a terminating "one". The code contains  $2^n$  entries (code words) of fixed length  $n$ . The entries are of two types: Type 1 entries represent "zeros" with a terminating "one" and Type 2 entries represent strings of consecutive "zeros". For a high resolution digitized engineering drawing (3000 x 4000 pixels), Bradley finds the theoretical performance of his coding technique produces a compression ratio of 13.2. He compares his approach to a run-length coding scheme which provides a compression ratio of 8.65 by using a fixed length code of  $\log_2 3000$  bits to encode each run regardless of its probability. The maximum compression ratio based on the entropy of the source is 17.58. Of course the run-length coding technique could be improved by using Huffman coding, but then this makes the coding source dependent.

The optimized form of run-length coding seems attractive for binary sources but its application to the case of multilevel sources does not seem appropriate.

2. Encoding of the Changing Elements - This coding technique, considered for two-level data as well as continuous-tone imagery, transmits only the changing elements along with the addressing information as to where the change occurred. Various implementations of this technique are discussed in the literature. Ehrman considers three different versions of this technique and employs them for redundancy reduction along

either the horizontal or vertical direction for intraframe coding of continuous-tone pictures<sup>(43)</sup>. Mount uses the technique along the temporal axis for intraframe coding of picturephone signals<sup>(44)</sup>. This system is desirable since a threshold level can be chosen such that only changes above that level are detected. This increases the compression ratio and eliminated background noise. This technique, when applied to two-level sources, would use a zero threshold to provide distortionless encoding. The performance of this technique for two-level sources is inferior to run-length coding if a PCM Coder is used to encode the addressing information; however, more sophisticated schemes, such as one similar to the Cluster Coding<sup>(45)</sup>, might make this technique more efficient. This technique seems attractive for the case of multilevel sources.

3. Facsimile Coding by Shipping White - Most documents and line drawings contain a large amount of white space. One approach to their efficient coding is to skip the white space. A simple way of doing that was suggested by de Coulon and Kunt<sup>(46)</sup>, and Horlander<sup>(47)</sup>. Each sampled scan line is divided into N-picture-element (pel) blocks. For a block containing at least one black pel, we use an  $(N+1)$  -bit code word, the first bit being "1" and the next N bits being the binary pattern of the N-pel block in question. For example, if  $N = 4$  and a block contains two white pels followed by two black pels, then the code word for that block is "10011". Here we have used "0" to represent white and "1" black.

Once a value for N is fixed, the optimum code for the  $2^N$  possible N-pel patterns is of course the Huffman code based on the probability distribution on these patterns. However, the implementation of a Huffman code is complicated. If the image contains a large amount of white, then the Horlander-de Coulon-Kunt (HCK) code may perform almost as well as the Huffman code and is much simpler to implement.

For a given image or class of images, the average bit rate  $b_N$  (bits/pel) of the HCK code depends on the block size N. Some theoretical results for choosing N to minimize the bit rate are available<sup>(48)</sup>. Huang has modified the HCK code for improved performance and reports that the modified HCK code is comparable to runlength coding for texts, but runlength coding is more efficient for line drawings and weather maps<sup>(48)</sup>.

HCK codes can also be used for bandwidth compression of multilevel graphics. For this application, each sampled scan line is divided into blocks containing N picture elements. A block of all white picture elements is encoded with a "0" and the other blocks are encoded by  $(mN+1)$  bit code words, the first bit being a "1" and the next mN bit are the actual pixel values. The compression ratio depends upon the total number of all white blocks in the document.

### 3.3.2 Two-Dimensional Techniques

The second class of facsimile coding techniques use the correlation of data in more than one spatial direction. The major two-dimensional techniques are:

1. Block Coding Technique - In this technique, the picture is divided into blocks of  $n \times m$  arrays, the message space consists of  $2^{mn}$  possible patterns per block. Each pattern is assigned a code word using a Huffman code based on the statistics of the data. Huang has considered this technique and has compared it to a run-length coding technique for various values of  $m$  and  $n$ . His results show that this technique is inferior to the run-length coding.

2. Predictive Differential Quantizing - This scheme makes use of the correlation between scan lines, and can be considered as an extension of run-length coding to two dimensions. Here the differences between corresponding run lengths of successive scan lines are transmitted. In applying this technique to encode weather maps and printed material, Huang concludes that it outperforms both run-length coding and block coding techniques when used on weather maps but it is inferior to run-length coding when used for printed material. This technique also can be modified to encode multilevel data; however, it is rather complicated and does not seem to hold much promise.

3. Contour Tracing Algorithm - This class of algorithms is truly a two-dimensional coding scheme. A contour tracing algorithm is suggested by Wilkins and Wintz<sup>(49)</sup> which traces the outer boundary of the largest connected set of elements having the same value as the initial point and always terminates back at the initial point. Wilkins and Wintz constrained the direction of travel to only four spacial direction to limit the direction information to 2 bits. All elements enclosed by the contour and having the same value as the contour are neglected but can be reconstructed at the receiver. The authors used Huffman codes for encoding the transmitted data and simulated the system for a number of continuous-tone and two-level imagery. This scheme performs particularly well for the case where the number of levels is about 8 to 32 levels, therefore, it is promising for encoding multilevel data. Its shortcomings are the large memory requirements and relative complexity of the contour tracing algorithms.

4. Two-Dimensional HCK Codes - The one-dimensional HCK codes discussed in 3.1.3 can be modified for two-dimensional data. One modification considers blocks of  $M \times N$  samples. For a block consisting of all white pels, the 1-bit code word "0" is used. For a block that consists of at least one black pel, an  $(M \times N + 1)$  bit code word is used, where the first bit is "1" and the next  $M \times N$  bits are the binary pattern of the  $M \times N$  pel block. The technique also applies to multi-level imagery by again using "0" for all white blocks and using "1" following by  $M \times N \times \log_2 m$  bits for the blocks with at least one non-white pel. Here  $m$  is the number of grey levels per pel and it is assumed that  $\log_2 m$  is an integer.

#### 4. DIGITAL COMPRESSION SYSTEMS FOR SHUTTLE TV

In this section the characteristics of the Field-Sequential Color TV and the slow scan uplink system are discussed. Based on the characteristics of these signals and a rather severe weight-power limitations on the encoder or decoder, a number of bandwidth compression techniques, compatible with the Shuttle requirements, are chosen as candidate techniques. Based on the performance and the complexity of the candidate systems, a 2D-DPCM technique is recommended for the downlink system and a two-dimensional HCK facsimile coding technique for the low data rate uplink system.

##### 4.1 CHARACTERISTICS OF SHUTTLE IMAGERY

The Shuttle will be using the Apollo Color Television System in the first few missions for downlink transmission of pictorial data. The present plans call for using a standard three-camera color television system for future missions. The uplink system will transmit high resolution imagery in slow scan format. The spatial and grey level resolution for various modes of operation of the slow-scan system are described in Section 4.1.2. Although the future plans for the Shuttle downlink system calls for a three-camera color camera, in this study bandwidth compression for the Field-Sequential Color TV system is emphasized. This is because the characteristics of the Field-Sequential Color TV system are markedly different from the characteristics of both monochrome and commercial color television. Therefore, the bandwidth compression techniques developed for commercial television are not adequate for compressing the bandwidth of Field-Sequential Color Television.

##### 4.1.1 Field-Sequential Color Imagery

The Field-Sequential Color TV system uses a modified monochrome TV camera with a rotating color wheel. The rotating color filter exposes the camera image tube sequentially, at the commercial broadcast scan rate, to the red, blue, and green components of a scene. Therefore sequential fields differ in spectral components in addition to the field-to-field variations caused by temporal motion. This generates spectral and temporal correlation in addition to the spatial correlation inherent in all pictorial data. However, due to spectral variations, the relative degree of the total spectral and temporal correlation of the Field-Sequential Color TV is less than the temporal correlation between the sequential fields of monochrome television. Therefore one can not achieve as high of a bandwidth compression with Field-Sequential color TV as one achieves with monochrome television for the same image fidelity.

The bandwidth of the Field-Sequential signal is significantly smaller than the bandwidth of a standard color TV system. This is because the standard NTSC color television uses three color guns, each with the same bandwidth as the camera used in Field-Sequential color TV system. However, the signal generated by NTSC color television system exhibits more temporal and spectral correlation; therefore its bandwidth can be compressed by a larger ratio.

The Field-Sequential color TV images used in this study were generated from a camera with a bandwidth of about 4.2 MHz. The minimum sampling frequency is about 9 M samples/second. Experimental results with commercial television has shown that excellent image quality results when the sampling rate is set to generate 512 samples for the active duration of each TV line.<sup>(5)</sup> Although there are only 240 active lines per field in commercial TV, we have digitized 256 lines per field and will report the equivalent bandwidth transmitting all 256 lines. The output of Field-Sequential Color TV camera was recorded on video tape and then digitized. Digitization of the video data was performed at EG&G Corporation in Los Alamos, New Mexico.

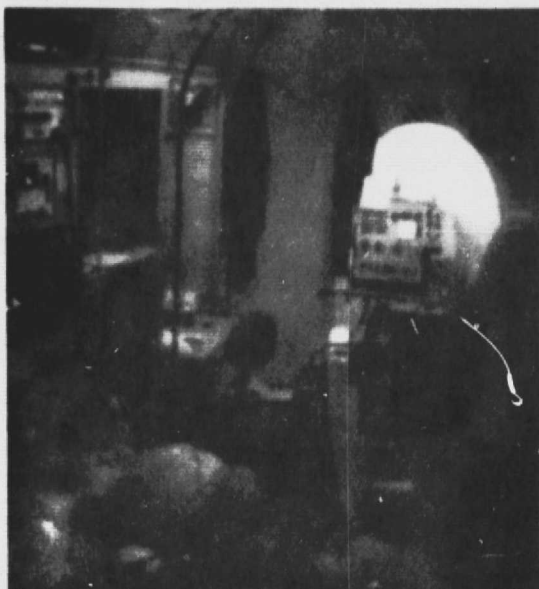
The digitization procedure requires taking two sequential fields from the video tape and transferring them to an analog disk. The stored frame is then time base corrected and digitized column-wise to a grey-level resolution of 8 bits per sample and 512 samples per line. The digitized data is then stored on a computer compatible magnetic tape. Before processing by bandwidth compression software, the digitized imagery stored in the form of a 512 by 512 matrices is transposed to make each individual image available in a line-to-line format. This is essential since normal TV imagery is scanned in a line-to-line format.

The sampling and A/D conversion of the television signal performed at EG&G Inc. limits the digitized image signal-to-noise ratio to 32 dB. The digitized data is then bandwidth compressed using the recommended bandwidth compression technique simulated on an Interdata-85 Computer and is returned to EG&G Inc. for conversion to a video tape format. The inverse operation also introduces noise in the reconstructed signal.

Figure 4-1 shows two typical frames of the Field-Sequential TV data at a spatial resolution of 512 by 512 samples. Figure 4-1(a) is generated by interlacing Blue-Green and Figure 4-1(b) is generated by interlacing Red-Green fields. Naturally two interlaced fields are separated by  $\frac{1}{60\text{th}}$  of a second and on the monitor they would be viewed  $\frac{1}{60\text{th}}$  of a second apart.

#### 4.1.2 Slow-Scan Imagery

NASA is considering a slow-scan high-resolution system for transmitting pictorial data from ground station to the Shuttle. At present a slow-scan system with four modes of operation is under consideration. The specifications of these four modes are listed in Table 4-1. As indicated in this Table, two modes of operation produce a binary grey-scale while the other two modes produce a grey scale composed of 64 levels.



(a) Interlaced Blue-Green Fields



(b) Interlaced Red-Green Fields

Figure 4-1. Two Typical Field-Sequential Color Interlaced Fields

Table 4-1. Image Resolution for Various Modes of Operation for 8" x 10" Images. Transmission Time is for an Uplink Channel of 144K bits/second.

Modes of Operation	Spatial Resolution Lines per Inch	Grey Level Resolution Bits/Sample	Transmission Time (Minutes)
1	125	1	0.14
2	250	6	3.47
3	350	1	1.13
4	500	6	13.89

NASA/JSC has supplied TRW with a number of diagrams and graphics to be used for evaluating our simulated slow-scan uplink bandwidth compression system. The originals, shown in Figure 4-2, are typical of the material that is expected to be transmitted to the Space Shuttle. These images were digitized at 8 bits per sample. The scanning aperture was about 100 micron square which generated around 1024 by 1024 samples per frame. The original scanned and digitized frames were then converted to a binary grey scale. These are shown in Figure 4-3. These figures represent a spatial resolution of about 350 scanned lines per inch which is equivalent to "mode 3" of the proposed slow-scan system. Low resolution images (120 scan lines per inch) are produced on the computer from the high resolution frames. This is done by generating an image composed of every third sample and every third line. The low resolution images are shown in Figure 4-4. Inspection of these figures shows that the lower resolution (120 lines per inch) is not acceptable for most ordinary documents).

#### 4.2 IMAGE BANDWIDTH COMPRESSION SYSTEM EVALUATION

To evaluate the performance of a particular bandwidth compression method, one must determine whether the bandwidth compression method preserves sufficient information for a given application. To do this, a criterion of optimality must be defined by which the information loss is measured. To measure the distortion in imagery, a variety of criteria of optimality have been used. These criteria are necessarily user-dependent. One such criterion is the weighted mean square error used in conjunction with video data. This measure weights the error at various frequencies according to the characteristics of human vision. The imagery data used for applications involving pattern recognition and pattern classification use other measures such as the classification accuracy of the compressed imagery. In addition to these criteria, which are used to evaluate the performance of a bandwidth compression technique, a different set of criteria exists which relate to the complexity, cost, and the sensitivity of various image bandwidth compression technique to sensor and channel transmission errors. These criteria are discussed under the general heading of the system considerations. They are also of varying degrees of importance depending upon the particular application.

In this study the criteria of optimality we use are mean square error, peak-to-peak signal to RMS noise ratio, subjective quality, and the system complexity.

##### 4.2.1 Mean Square Error and Signal-to-Noise Ratio

Mean square error is the most frequently used criterion of optimality in data compression as well as in most other estimation and filtering problems. This is partly due to the inherent simplicity of this criterion which allows for closed-form analytical solutions and partly to the fact that many sensing systems respond directly to the energy contained in the stimulus and that the energy and mean square error are closely related. Many image bandwidth compression results are in terms of mean square error or weighted mean square error.

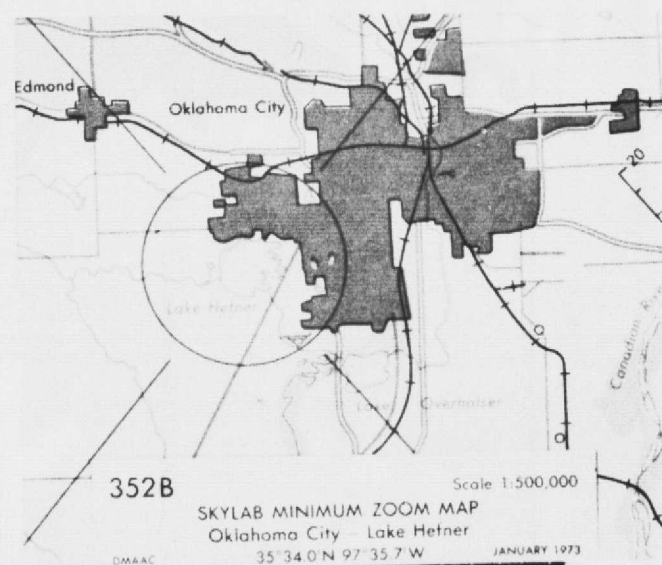
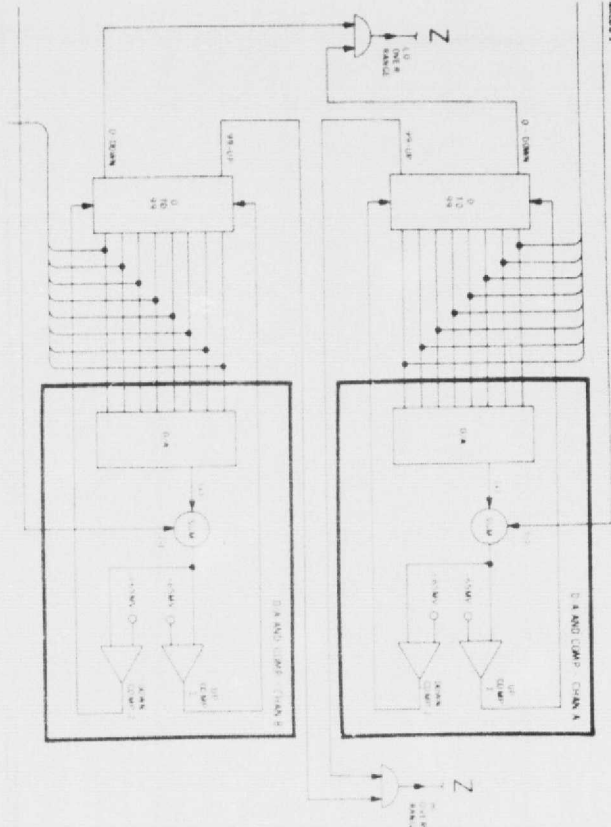
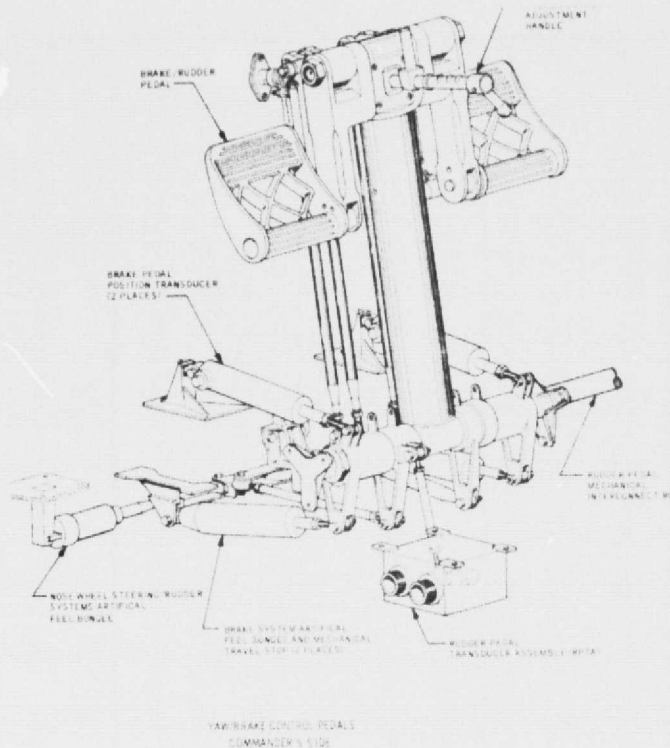
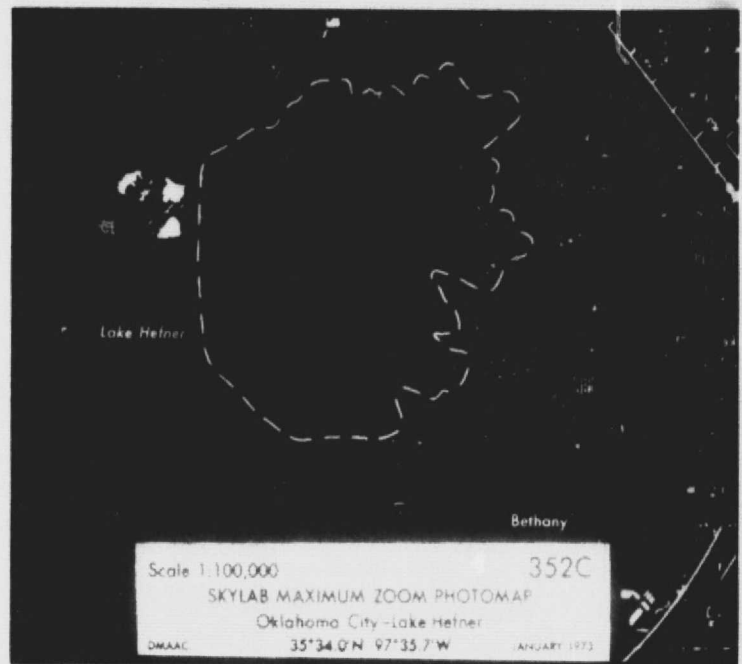
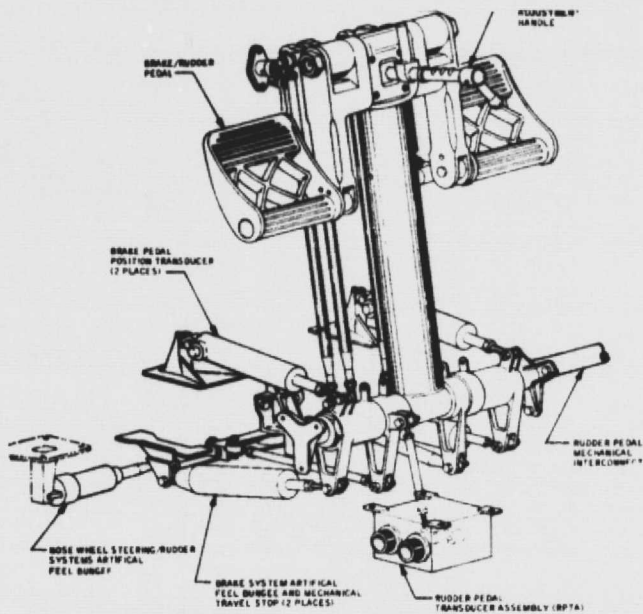


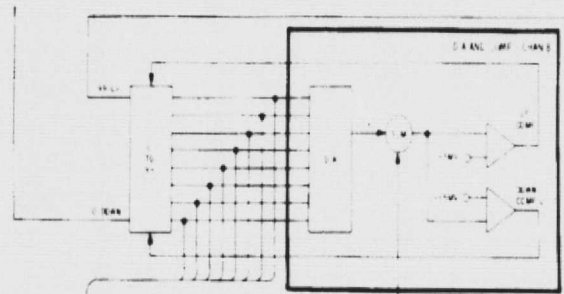
Figure 4-2. Typical Slow-Scan Uplink Imagery



### Responsibilities of the Contractor

The contractor shall keep the equipment in good rating condition and always shall be responsive to the maintenance requirements of the Government.

Remedial maintenance shall be performed upon notification that equipment is inoperative. The contractor's maintenance personnel shall complete repairs within 24 hours after notification by the Government that remedial maintenance service is required. Failure to comply with this requirement will result in deductions of maintenance charges on basis of 1/30th of the monthly rate for each day.



REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

Figure 4-3. Digitized Binary Imagery with 1024 x 1024 Samples



#### 4.2.2 Subjective Quality

An important criteria in evaluating the performance of bandwidth compression techniques is the subjective quality of the reconstructed imagery. In this sense the cosmetic quality of the bandwidth compressed signal is as important as its quality evaluated using some analytical measures. Unfortunately, the Field-Sequential color TV signal is generated by a modified TV camera and the signal can be viewed in full color only when it is replayed on a modified video playback unit. For this reason it was impossible for us to optimize the bandwidth compression technique for color fidelity. However, we have used all precautions to preserve the color quality. The final demonstration of the selected bandwidth compression technique will involve displaying 10 seconds of the bandwidth compressed signal along with the original signal on a modified video player.

Individual frames of the field-sequential color TV data are in black and white. Subjective evaluation of the bandwidth compression algorithms was performed on individual frames by viewing the reconstructed data on a COMTAL Image Display and by comparing Polaroid pictures that were generated from the original and reconstructed imagery on a DICOMED film writer.

#### 4.2.3 System Complexity

In addition to the criteria of optimality which are used to evaluate and compare the performance of various techniques, there exists a different set of criteria which deals with the systems aspects of the various techniques. This set of criteria is particularly important in the hardware design and operation of the system.

In the present study, the major constraints are the severe weight and power limitations. For the downlink system, the design of the processing that proceeds the encoding operation as well as the choice of the proposed encoder are compromised to satisfy these constraints. That is to say that the same reconstructed image fidelity could have been achieved at lower bandwidths if one did not have to satisfy the present constraints on weight-power requirements of the encoder. Similar considerations are required for the decoder used with the uplink system.

#### 4.3 GENERATION OF FIELD-SEQUENTIAL COLOR TV SIGNAL COMPONENTS

The characteristics of the Field-Sequential Color TV signal was discussed in Section 3.2. The salient feature of the Field-Sequential Color TV signal is that the sequential fields exhibit temporal as well as spectral correlation and exploiting those correlations in addition to spatial correlation is essential to the efficient bandwidth compression of the Field-Sequential Color TV. Spectral correlation is best

utilized by using red, green, and blue fields to generate the illuminance (Y) and the chromaticity components (I, Q). These are related to the red, green and blue components of the color signal as follows:

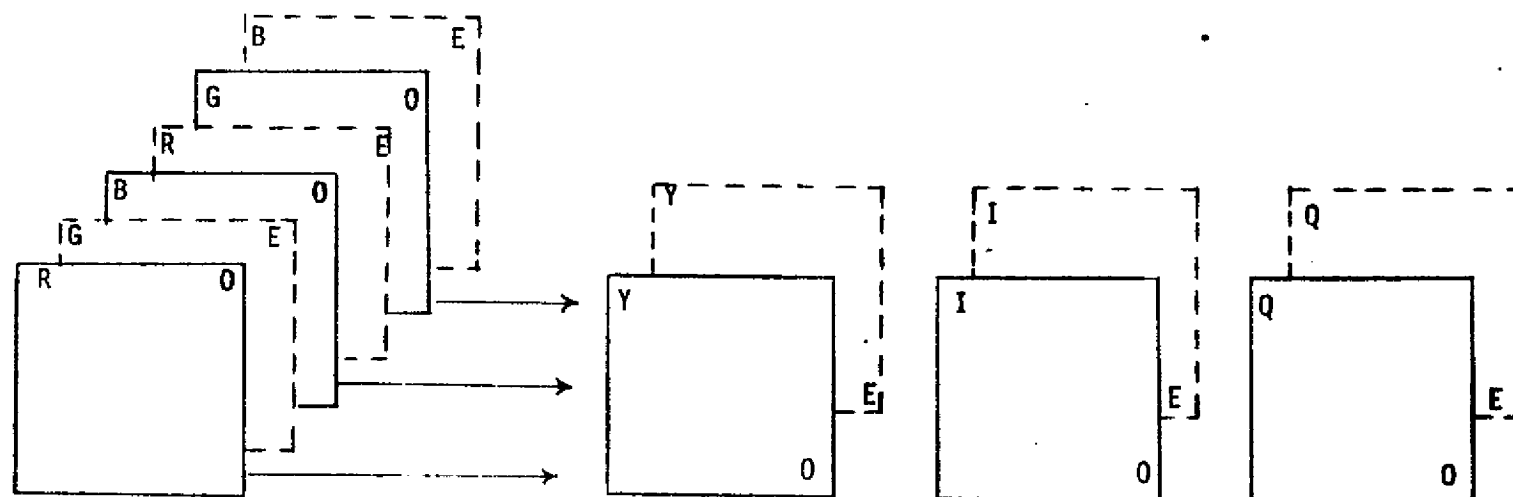
$$\begin{aligned} Y &= 0.30 R + 0.11 B + 0.596 G \\ I &= 0.74 (R-Y) - 0.027 (B-Y) \\ Q &= 0.48 (R-Y) - 0.41 (B-Y) \end{aligned} \quad (4.1)$$

Sequential fields of the Field-Sequential Color TV signal are composed of the odd and even lines as shown on Figure 4-5.

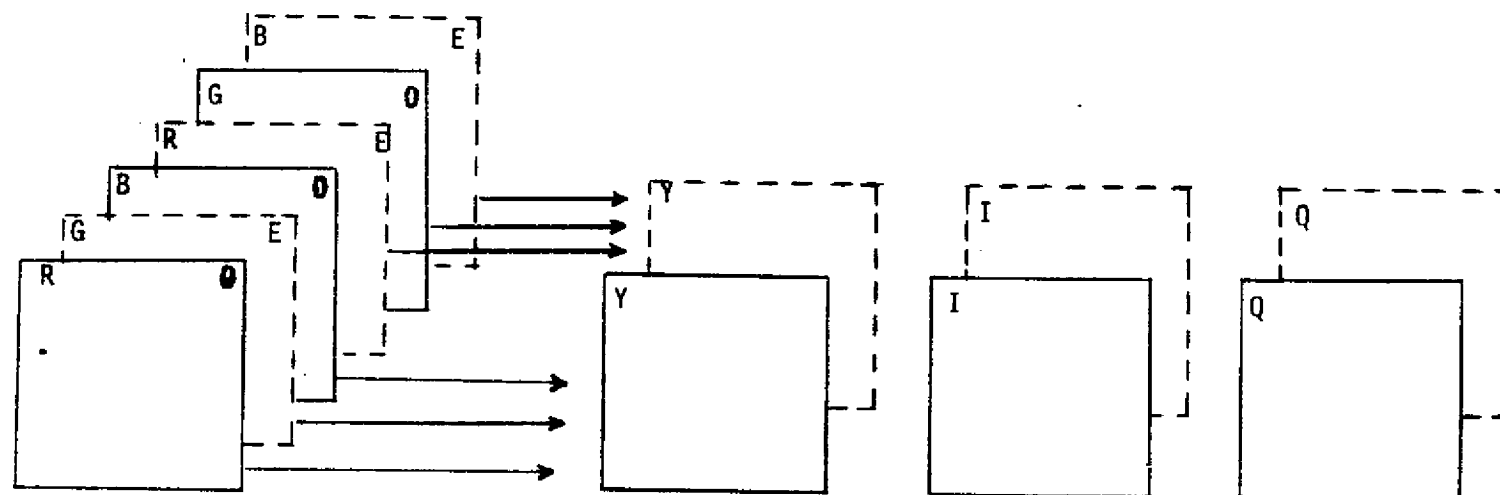
In combining red, green, and blue components to generate Y, I, and Q, one utilizes the correlation of the spectral components for a maximum compaction of energy in the illuminance signal. A spectral compaction that results from identical signals for the red, green, and blue components produces a maximum value illuminance and a zero grey level for the chromaticity components. On the other hand, the most dissimilar red, green, and blue signals will result in an identical signal for the illuminance and the chromaticity components. In Field-Sequential Color TV, the sequential fields are composed of odd and even lines. The odd red field exhibits spectral similarity with the odd blue and odd green fields. However, these samples are separated by a temporal distance of  $4/60$ th of a second and this causes some spectral decorrelation due to temporal motion. The Y, I, and Q signals formed from all-odd or all-even frames, which requires storing a minimum of 4 frames, are particularly susceptible to spectral decorrelation from rapid temporal motion. An alternate procedure is to mix the odd and even fields in generating the illuminance and the chromaticity components. This requires storing only two fields. The mixing of the odd and even fields results in a smaller correlation among the spectral components but a larger temporal correlation, since the three fields used in generating Y, I, and Q are only  $\frac{2}{60}$ th of a second apart. This gives a larger or smaller compaction of energy in the illuminance signal depending upon the comparative size of spectral similarity and temporal motion. In this study we choose a mixing of the odd and even fields in generating illuminance and chromaticity component mainly to reduce the memory requirements.

In addition to the mixing of the even and odd fields, we propose other modifications to reduce the memory requirements further. Although the Y, I, and Q signals used in the United States Commercial Television lead to the most efficient analog TV bandwidth compression, the European TV systems use a different set of chromaticity components which are useful alternatives for digital bandwidth compression applications. These are related to red, blue and illuminance components as follows:

$$\begin{aligned} C_1 &= R-Y \\ C_2 &= B-Y \end{aligned} \quad (4.2)$$



(a) Combining Odd and Even Fields Separately to Generate Y, I, and Q Signals.



(b) Combining Odd and Even Filters to Generate Y, I, and Q Signals

Figure 4-5. Statistics of the Field-Sequential G, R-G, and B-G Fields

The attractive feature of these chromaticity components are that they can be generated using only a single field of memory if the illuminance signal is directly available. This presents two set of alternatives that can be explored for design simplifications.

#### 4.3.1 Possible Color Wheel Modifications

Using the European system one can replace the green filter in the color wheel by a "colorless" filter to obtain the illuminance signal directly. Then only one field of memory is required to generate the  $C_1$  and  $C_2$  components. The functional diagram of the proposed system is shown on Figure 4-6. The only concern regarding the characteristics of the "colorless" filter is that it must have a frequency response such that the illuminance signal would have the same characteristics as that of the Y signal obtained from R, G, and B components.

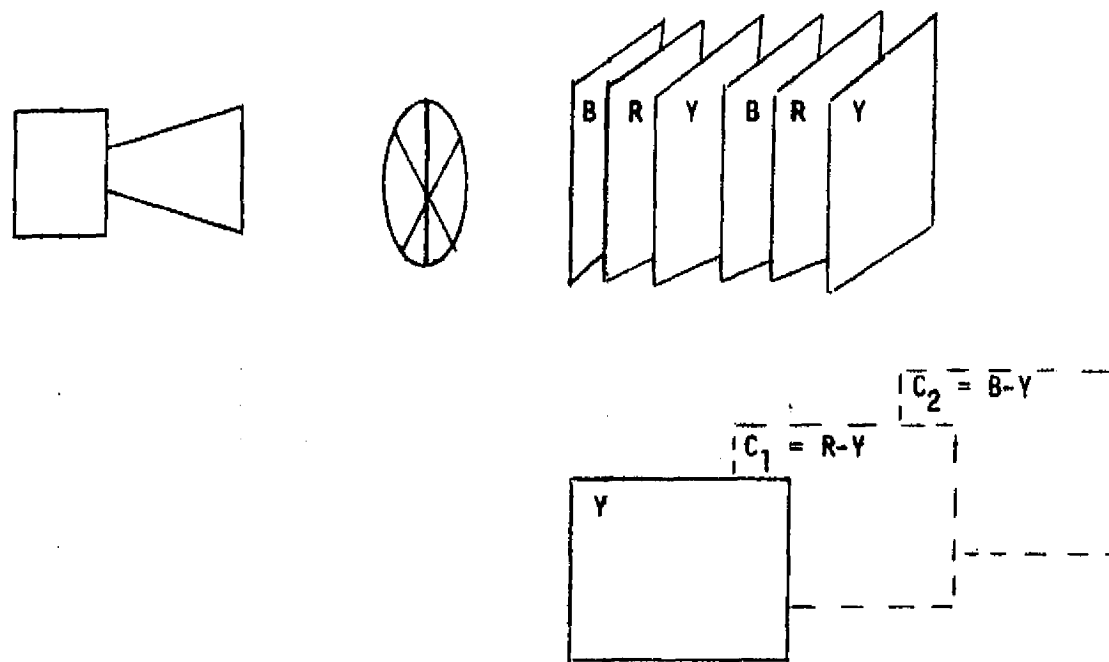


Figure 4-6. Functional Diagram of the Modified System. Only Y Fields Need to be Stored.  $C_1$  and  $C_2$  Fields are Generated from Incoming R and B Fields and are Transmitted

#### 4.3.2 Using Green Component Instead of Illuminance

A second approach, with attractive implementation properties, uses the standard color-wheel and substitutes the green field for the illuminance signal. Then the chromaticity components are obtained by subtracting the green from the red and the blue components. This approach is based on the fact that the green spectral component is very similar to the illuminance component for TV signals. Also, the green component possesses more energy and shows more details than the red and blue components. Using the green component instead of the illuminance, the transmission tristimulus signals are

$$\begin{aligned}\hat{Y} &= G \\ \hat{C}_1 &= R-G \\ \hat{C}_2 &= B-G\end{aligned}\tag{4.3}$$

$\hat{C}_1$  and  $\hat{C}_2$  possess a much smaller bandwidth and a smaller fraction of the signal energy than the G component; therefore, they can be transmitted in a subsampled form utilizing a smaller fraction of the available bit rate.

#### 4.3.3 Recommended Color Signal Generation Approach

We recommend generating the tristimulus color components via equation 4.3. This approach substitutes the green signal for the illuminance signal and does not require modification of the color wheel. Since no results appear in the technical literature relating to this approval, we designed a number of experiments to evaluate the suggested system. Figure 4-7 shows reproductions of the 256 x 256 color pictures used to generate the illuminance and the chromaticity components for the NTSC system used in the United States, the system used by commercial television in Europe and the method suggested for the Shuttle TV application.

In each system the illuminance signal is used directly while the chromaticity components are subsampled. The chromaticity signals can be subsampled by taking every other sample without affecting the quality of the reconstructed signal since human vision is rather insensitive to color information at high frequencies. Transmitting the chromaticity components in subsampled form means that the reconstructed composite signal at the receiver has illuminance as well as the chrominance signals at low frequencies, but contains only the illuminance information at high frequencies. Subjective experiments with television viewers at normal viewing distances have indicated that this is in fact acceptable.<sup>(51)</sup>



ORIGINAL



I, Q SUB-SAMPLED 5:1



C<sub>1</sub>, C<sub>2</sub> SUB-SAMPLED 5:1



R-G, B-G SUB-SAMPLED 5:1

Figure 4-7. Original and Reconstructed Images Using Subsampled Forms of Various Chromaticity Components

The reconstructed composite signal is generated and is compared to the original using subjective quality as well as the mean square error (MSE) between the original and the reconstructed signal. The MSE results are shown in Table 4-2. The subjective results are almost identical and are shown in Figure 4-7. The reconstructed composite pictures shown square waves around the edges where the hue of the color changes. Most of this effect will not be noticed by viewer watching a color TV monitor due to the integration effect of human vision.

Table 4-2 shows that substituting green for illuminance results in a MSE of 40.33 as compared to a MSE of 29.44 for the European commercial TV. However, these results are for a subsampling by a factor of 5 to 1. Two-to-one subsampling results are also shown in Table 4-2. Using a subsampling of 2 to 1, the resultant MSE is about 50% less than at a subsampling rate of 5 to 1. The reconstructed picture at the subsampling rate of 2 to 1 using green for illuminance also shows better subjective quality than the picture reconstructed using the optimum system at a subsampling rate of 5 to 1. This is shown in Figure 4-8. Based on these results we expect that the green can be substituted for the illuminance in the proposed system and still maintain a high quality color composite image.

#### 4.3.4 Low-Pass Filtering of the Chromaticity Signals

Prior to subsampling the chromaticity signals, they must be filtered to eliminate their high frequency components to prevent aliasing. Although there exist sophisticated filtering techniques to eliminate the high frequency components of discrete signals, experiments with imagery data has shown that a simple 3-point "hanning" filter can be used with comparable results. A 3-point hanning filter uses weightings of 1/4, 1/2 and 1/4 to obtain the filtered signal as follows:

$$\hat{X}_{ij} = \frac{1}{4} X_{i,j-1} + \frac{1}{2} X_{ij} + \frac{1}{4} X_{i,j+1} \quad (4.4)$$

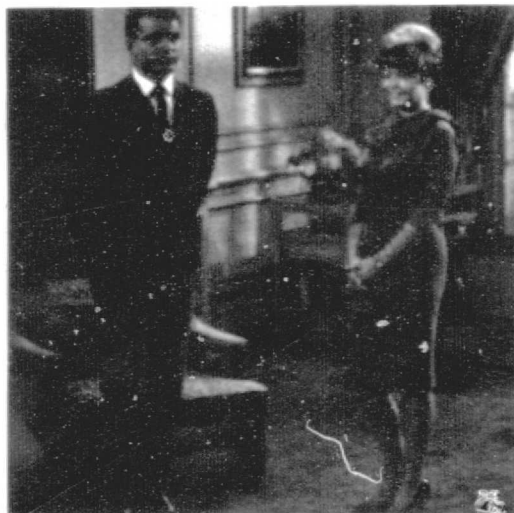
where  $\hat{X}_{ij}$  is the low-pass filtered form of  $X_{ij}$ . This filter is particularly attractive for digital signals since the multiplies can be performed by shift operations. In the proposed system the chromaticity signals are filtered by the 3-point hanning filter prior to a 2 to 1 subsampling of these signals.

#### 4.3.5 Candidate Field-Sequential Color Bandwidth Compression Techniques

A detailed study of bandwidth compression algorithms that process the G, R-g and B-G have lead to three candidate techniques. These are two-dimensional DPCM, adaptive two-dimensional DPCM, and the Hybrid system combining a Hadamard Transform with a DPCM encoder.

Table 4-2. MSE for a Subsampling Rate of 5:1 for Various Systems and the Proposed Shuttle System for a Subsampling Rate of 3:1 and 2:1

MSE	US Commercial TV (Y, I, Q) Subsampled 5:1	European Commercial TV (Y, C <sub>1</sub> , C <sub>2</sub> ) Subsampled 5:1	Substituting G for Y (G, C <sub>1</sub> , C <sub>2</sub> ) Subsampled 5:1	Substituting G for Y (G, C <sub>1</sub> , C <sub>2</sub> ) Subsampled 3:1	Proposed Shuttle System (G, C <sub>1</sub> , C <sub>2</sub> ) Subsampled 2:1
Red	43.213	42.732	83.638	34.074	25.416
Green	7.583	7.583	0.0	0.0	0.0
Blue	37.985	38.017	40.362	20.666	18.819
Average	29.93	29.44	40.33	18.24	14.74



SUB-SAMPLED 3:1



FILTERED, SUB-SAMPLED 3:1



FILTERED, SUB-SAMPLED 2:1

Figure 4-8. Reconstructed Images Using G and Subsampled Forms of R-G and B-G

#### 4.3.5.1 Two-Dimensional DPCM System

Two-dimensional DPCM systems were discussed in Section 3.1.2. The candidate technique we have selected uses a third order fixed predictor. The picture element  $X_{ij}$  is predicted using a linear combination of the adjacent element on the same line, the adjacent element on the same column and the element diagonally across from  $X_{ij}$  as follows:

$$\hat{X}_{ij} = 0.75 X_{i-1,j} + 0.75 X_{i,j-1} - 0.5 X_{i-1,j-1} \quad (4.5)$$

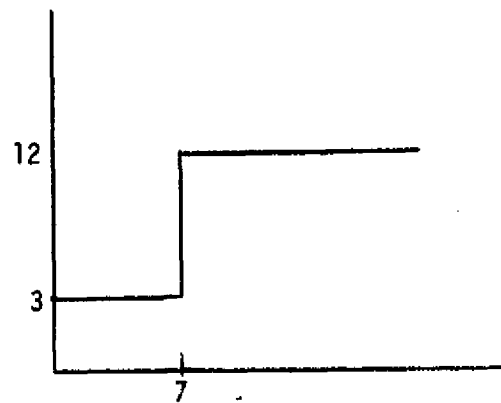
The fixed values of 0.75, 0.75 and -0.5 have been used for the weightings of the predictor since these weights provided the best overall results in the simulation studies. In addition, digital multiplication by these numbers can be performed by simple shift and add operations. The DPCM encoder uses two quantizers. One consists of 8 quantization levels and is used to encode the green signal component. The other consists of 4 quantization levels and is used to encode the chromaticity components. The cut points and output levels in the quantizer are selected for the best performance as measured by mean square error and the subjective quality of the reconstructed imagery. The two quantizer characteristics, which are symmetrical, are shown in Figure 4-9. For convenience, only the positive portion of the quantizer characteristics are shown in the figure.

#### 4.3.5.2 Adaptive Two-Dimensional DPCM Systems

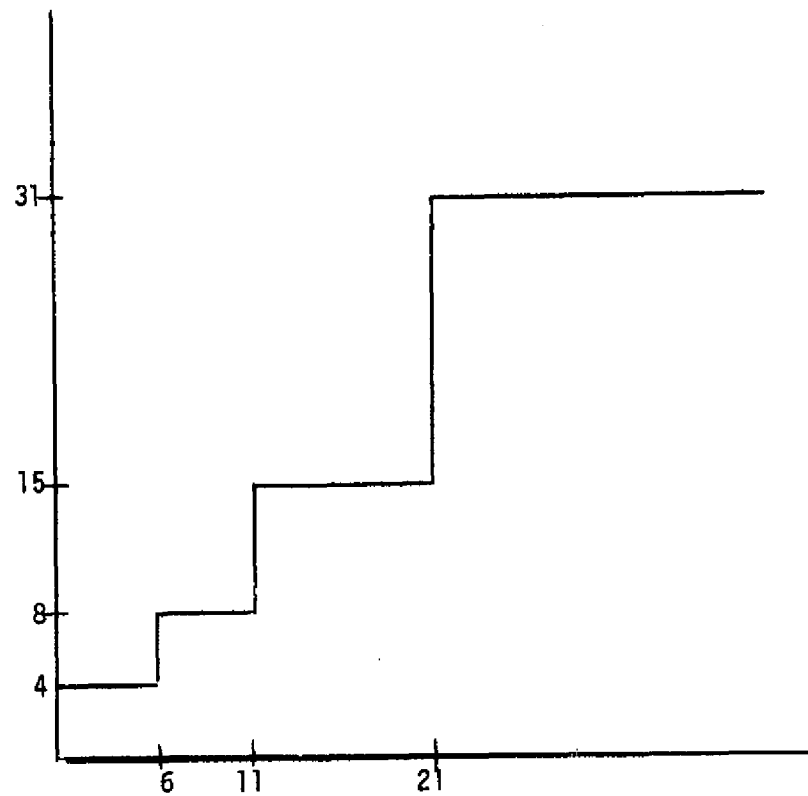
A number of adaptive two-dimensional DPCM encoders were surveyed in Section 3.1.2. Two adaptive two-dimensional DPCM systems are selected for further analysis. These are the block-adaptive DPCM encoder using multiple prediction loops and the block-adaptive DPCM system that uses a single prediction loop with a quantizer characteristic controlled by an auxiliary gain computation loop.

##### 1. Block-Adaptive DPCM Encoder Using Multiple Loops

The block diagram of the encoder is shown in Figure 4-10. Each DPCM loop uses a third order predictor defined by Equation 4.5. The quantizer in each loop has a different characteristic. The four quantizers are scaled versions of those shown in Figure 4-9. The scaling constants are 1/2, 1, 2 and 4. Each DPCM loop stores a block of 16 encoded samples in the shift registers and computes the total encoding error. The block select logic compares the distortion (total encoding error) for each loop and transmits the contents of that shift register which corresponds to the smallest distortion. The receiver needs information as to which DPCM loop was utilized for each block of data; therefore, two bits of overhead information are transmitted with each block indicating which loop (quantizer) was selected. This increases the bit rate by 1/8th of a bit per sample.



(a) 2-Bit Quantizer



(b) 3-Bit Quantizer

Figure 4-9. Positive Cut Points and the Reconstruction Levels of the Quantizers for the 2D-DPCM System

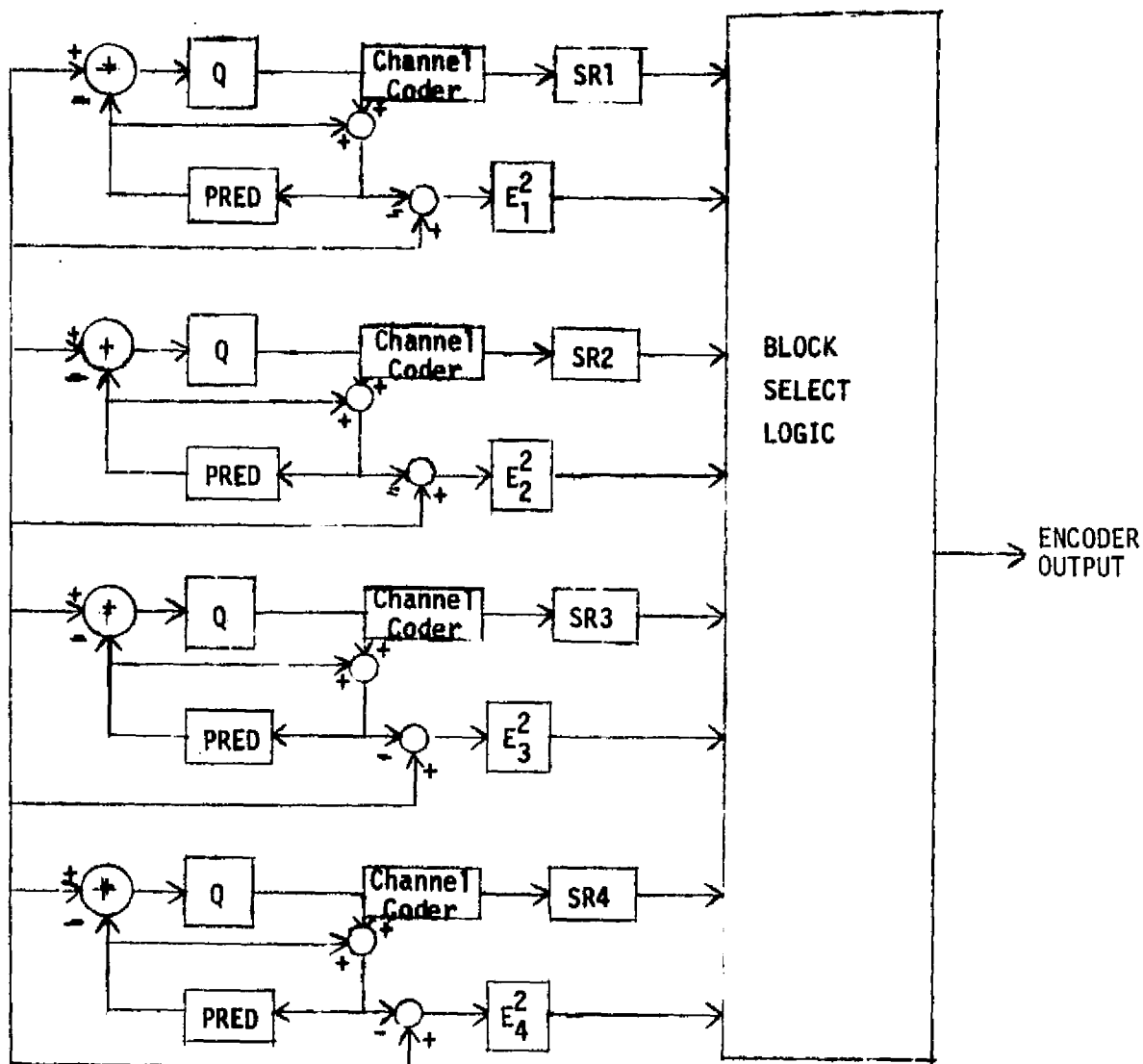


Figure 4-10. Block Adaptive 2D-DPCM System Using Multiple Loops

## 2. Block Adaptive DPCM Encoder Using a Single Loop

In principal this technique is similar to the adaptive DPCM system with multiple loops. Here a block of 16 samples is used in the gain computation loop (without a quantizer) to generate an estimate for the variance of the differential signal as shown in Figure 4-11. Depending upon the value of the variance, one of  $M$  gain factors are selected and are used to scale the quantizer characteristic in the prediction loop. We have used eight possible gain factors in this system ( $1/8$ ,  $1/4$ ,  $1/2$ ,  $1$ ,  $2$ ,  $4$ ,  $8$ ,  $16$ ). This requires  $3/16$ th of a bit per sample for transmitting this overhead information.

### 4.3.5.3 Hadamard Transform/DPCM System

Hybrid encoders use a concatenation of a unitary transform and a DPCM encoder. The hybrid encoder investigated in this study (Figure 4-12) uses a Hadamard Transform. A block size of four picture elements is used for simple implementation. Each Hadamard

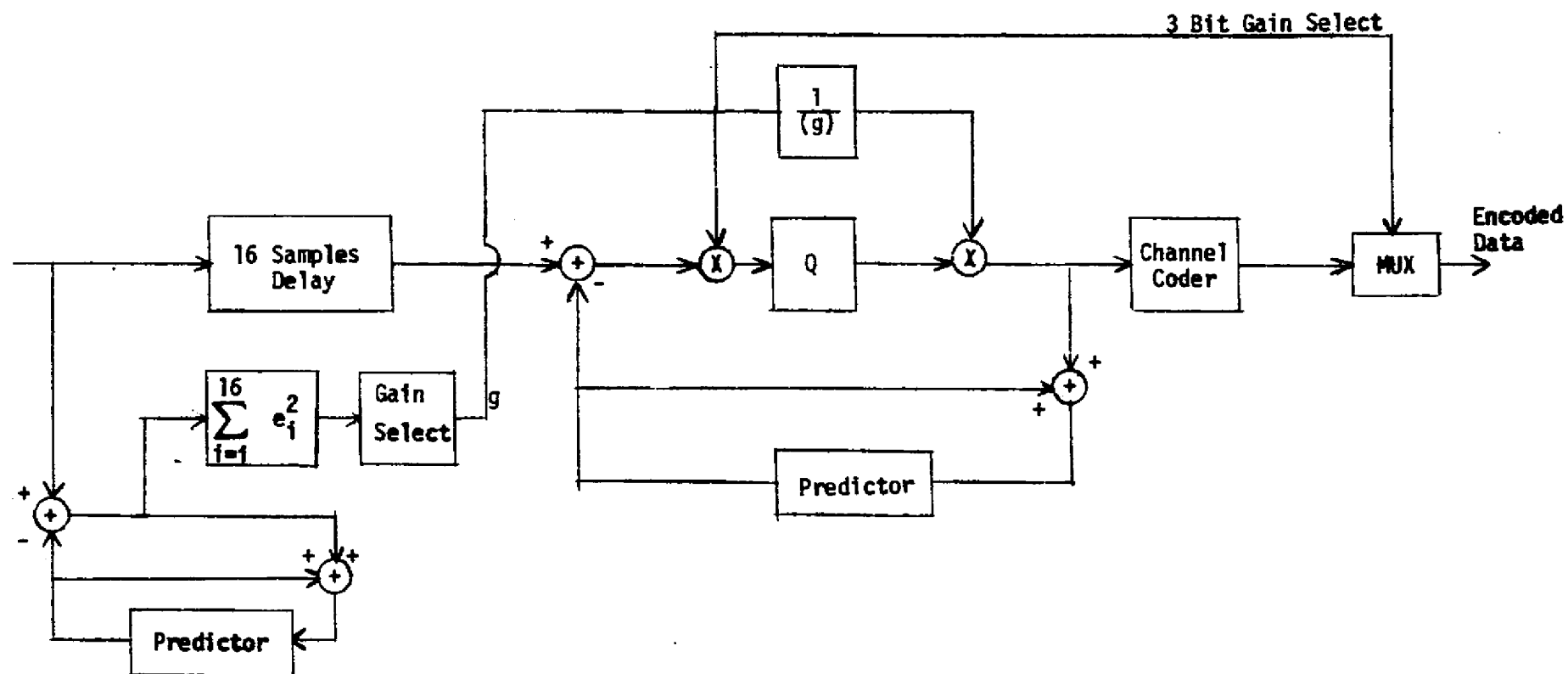


Figure 4-11. Adaptive DPCM Encoder Using a Single Loop

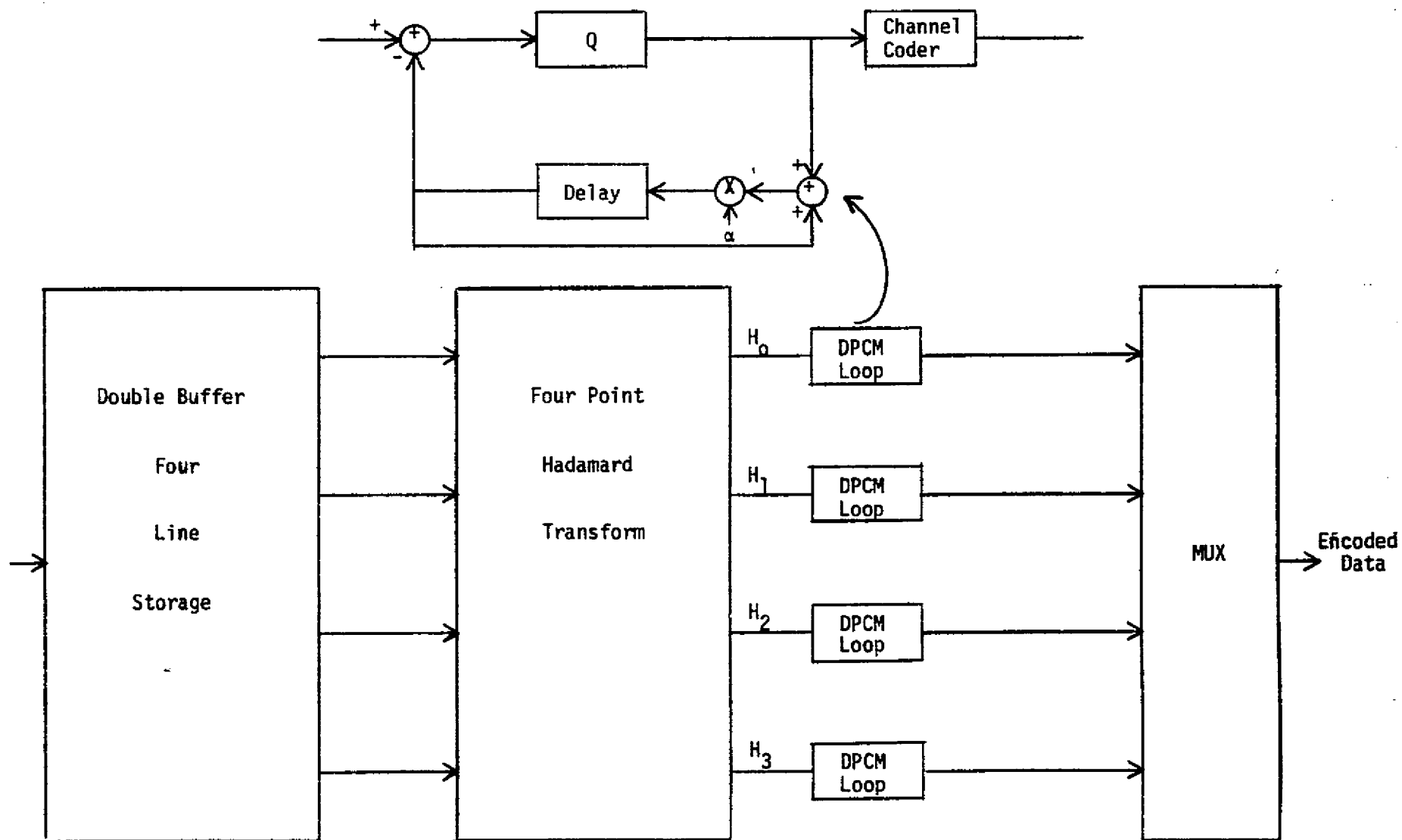


Figure 4-12. Hybrid Hadamard/DPCM Encoder

coefficient ( $H_0, H_1, H_2, H_3$ ) is encoded with a DPCM loop using a one element predictor with a fixed weighting coefficient. The bit assignment and weight coefficient for DPCM loop encoding the green signal and the chromaticity components are listed in Table 4-3. The quantizer in the DPCM loops are similar to those on Figure 4-9. However, the scaling of the threshold and reconstruction values for each loop is different. We have used scaling values of 2, 1, 1/4 and 1/4 for the DPCM loops encoding  $H_0, H_1, H_2$ , and  $H_3$ , respectively.

Table 4-3. Bit Assignment and Weighting Coefficients  
Per DPCM Systems in Hybrid Encoder

Type of Signal	Parameters	DPCM for $H_0$ Coeff.	DPCM for $H_1$ Coeff.	DPCM for $H_2$ Coeff.	DPCM for $H_3$ Coeff.
Green Field	Bits/Sample	4	3	3	2
	Weighting Coefficients	7/8	3/4	3/4	1/2
Chromaticity Signals	Bits/Sample	3	2	1	0
	Weighting Coefficients	3/4	3/4	1/2	1/2

#### 4.3.6 Algorithm Implementation Complexity

A major question in the evaluation and selection of a bandwidth compression algorithm for downlink transmission of video data from Shuttle is its implementational complexity. A number of processing techniques were rejected from consideration because of their complexity. In this section the complexity of the four candidate techniques are investigated. The results are presented in terms of number of integrated circuits and power required to implement each candidate technique. The processing that proceeds the coding of the signal as well as the buffering required at the output of the candidate encoders are sized separately and then summed to obtain the total system complexity.

##### 4.3.6.1 Non-Adaptive 2D-DPCM System Complexity

The two-dimensional DPCM system has been chosen as the baseline system for implementation comparison purposes.

Figure 4-13 illustrates the functional operation of the baseline encoder. Incoming digitized video information is brought in, and the difference between it and its predicted value is quantized by the fixed quantizer. The quantizer contains 8 symmetrically distributed cutpoints, each having its associated output value.

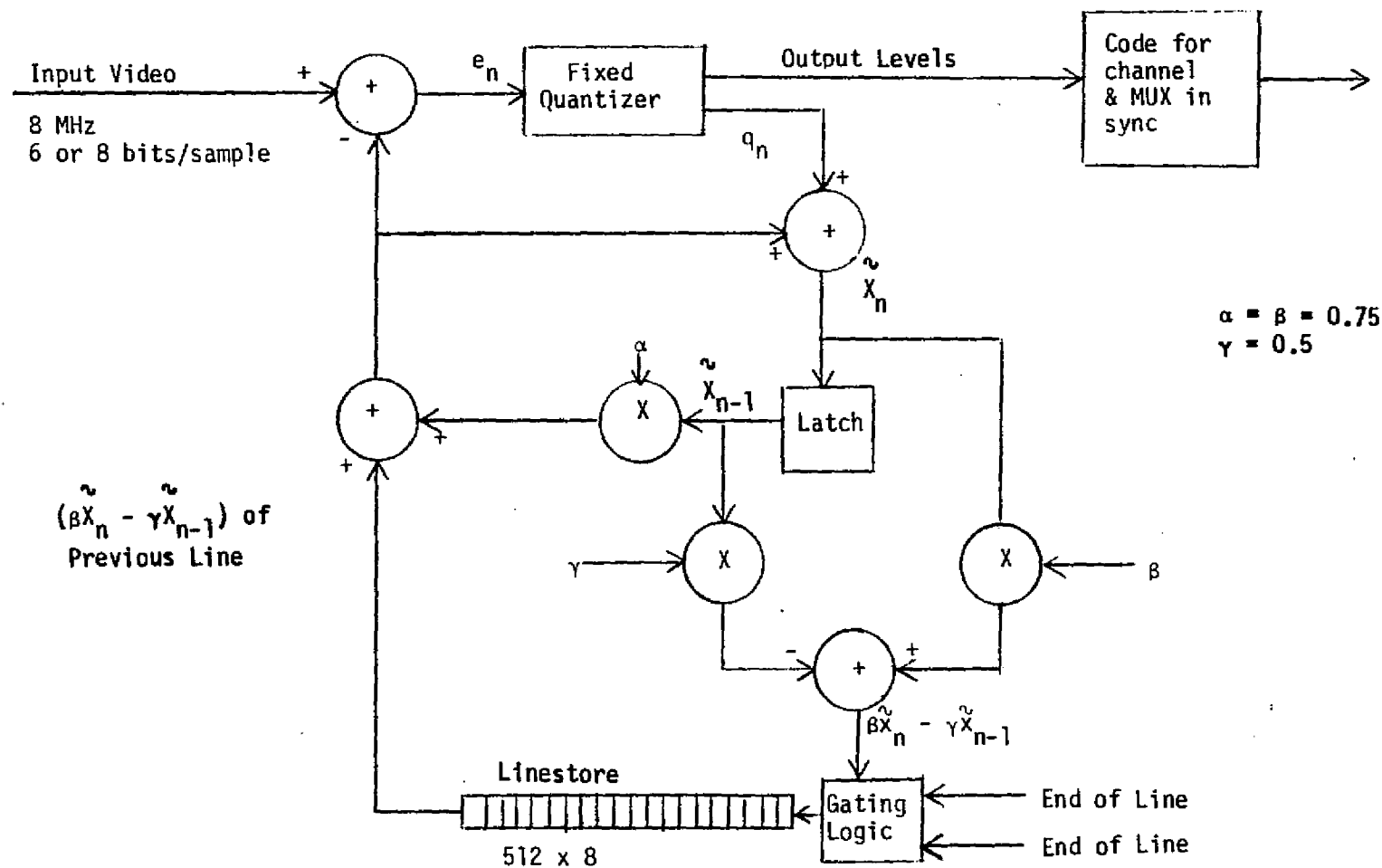


Figure 4-13. Nonadaptive 2D-DPCM Encoder

The output of the fixed quantizer is recoded for transmission, combined with synch information in a multiplexer, and supplied to the transmission link. Additionally, the fixed quantizer output is summed with the previous adjacent sample values, and stored for one sample time in a latch. Simultaneously the present and previous samples, from the line under consideration, are each scaled, and their difference stored in the Line Store Memory. Gating logic is provided such that samples are stored only during the active horizontal line time, and not during re-trace. The output of the Line Store Memory, representing the adjacent samples from the previous line, is summed with the scaled output from the latch (representing the adjacent sample from the line under consideration), and is subtracted from the next adjacent sample on the line under consideration.

Figure 4-14 illustrates the Non-Adaptive 2D DPCM Encoder implementation methodology. Synchronization circuitry is shown which accepts the camera system synch signals and generates all requisite system clocks and synchronization signals. The input analog video signal is A/D converted, and applied to the compressor loop. An important consideration in the proper operation of this loop is that processing should be completed in less than one sample time (125 nanoseconds). For this reason Emitter Coupled Logic (specifically, Motorola MECL 10,000) was chosen for the loop mechanization. Using this logic type, the worst case loop closure time is 116 nanoseconds. Where no speed penalty is incurred, the signals are translated to TTL levels, and lower power consumption elements employed (the One Line Storage Memory, and the Channel Coder and Mux).

#### 4.3.6.2 Adaptive DPCM System Complexity

Figure 4-15 illustrates the functional operation of the Multiple Loop Adaptive 2D-DPCM Encoder. This system utilizes four non-adaptive loops as previously shown in Figure 4-13. However, each loop is fitted with a different quantizer. The output of each loop is stored in a block storage register (16 samples). The Block Select Logic continuously calculated the Mean Squared Error for each block, at the sample rate. Upon completion of a block of data, the Block Select Logic selects for transmission the data block having the lowest Mean Squared Error.

Figure 4-16 illustrates the single loop block Adaptive 2D-DPCM Encoder which utilizes multiple quantizers. Here, a 16 sample (data block) delay is provided while the Gain Computation Logic determines the mean squared error and selects one of eight different quantizers within the Compressor Loop. Figure 4-17 shows the mechanization of this system. High speed ECL logic is required in both the predictor Logic and within the Compressor Loop.

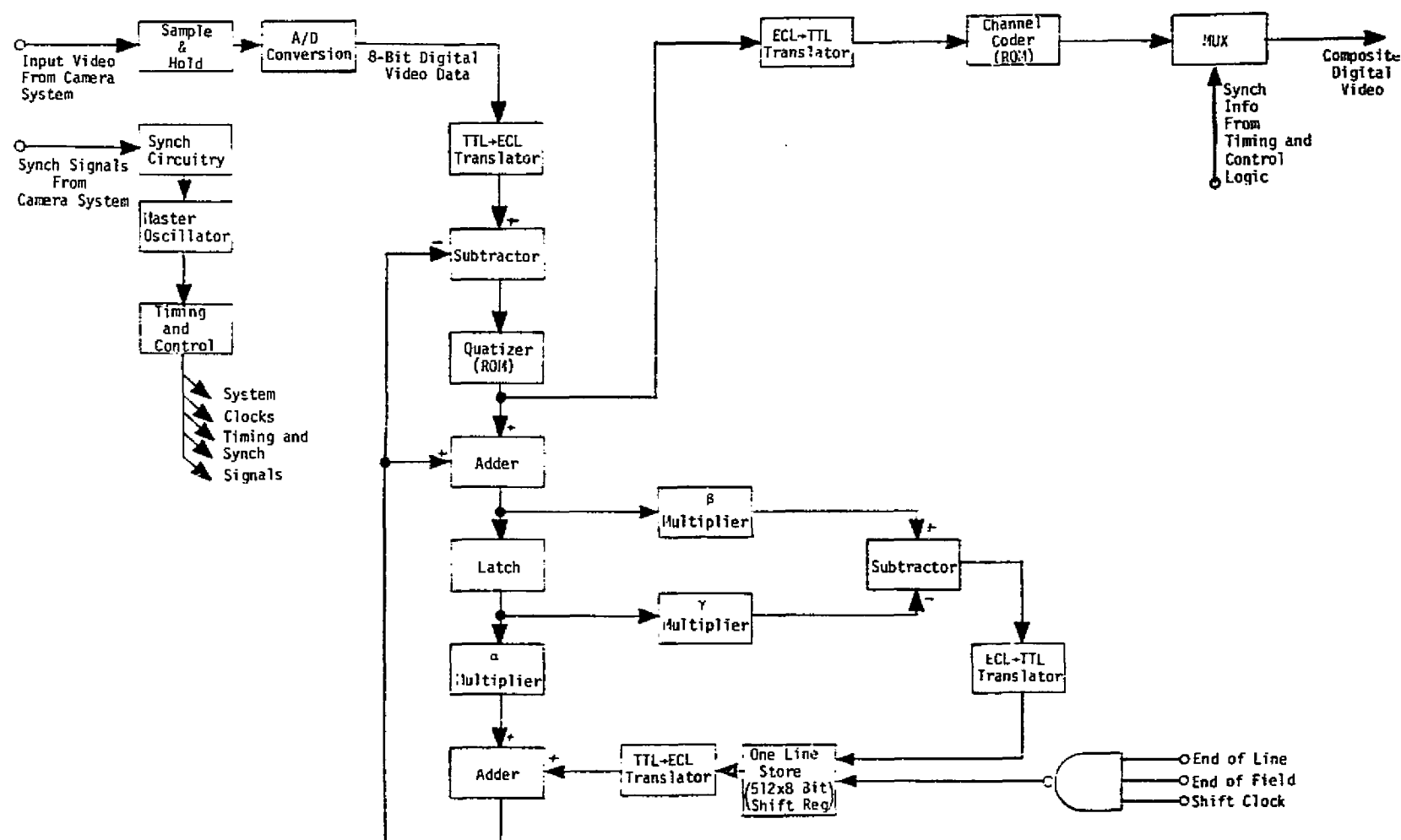


Figure 4-14. Implementation of the Nonadaptive 2D-DPCM Encoder

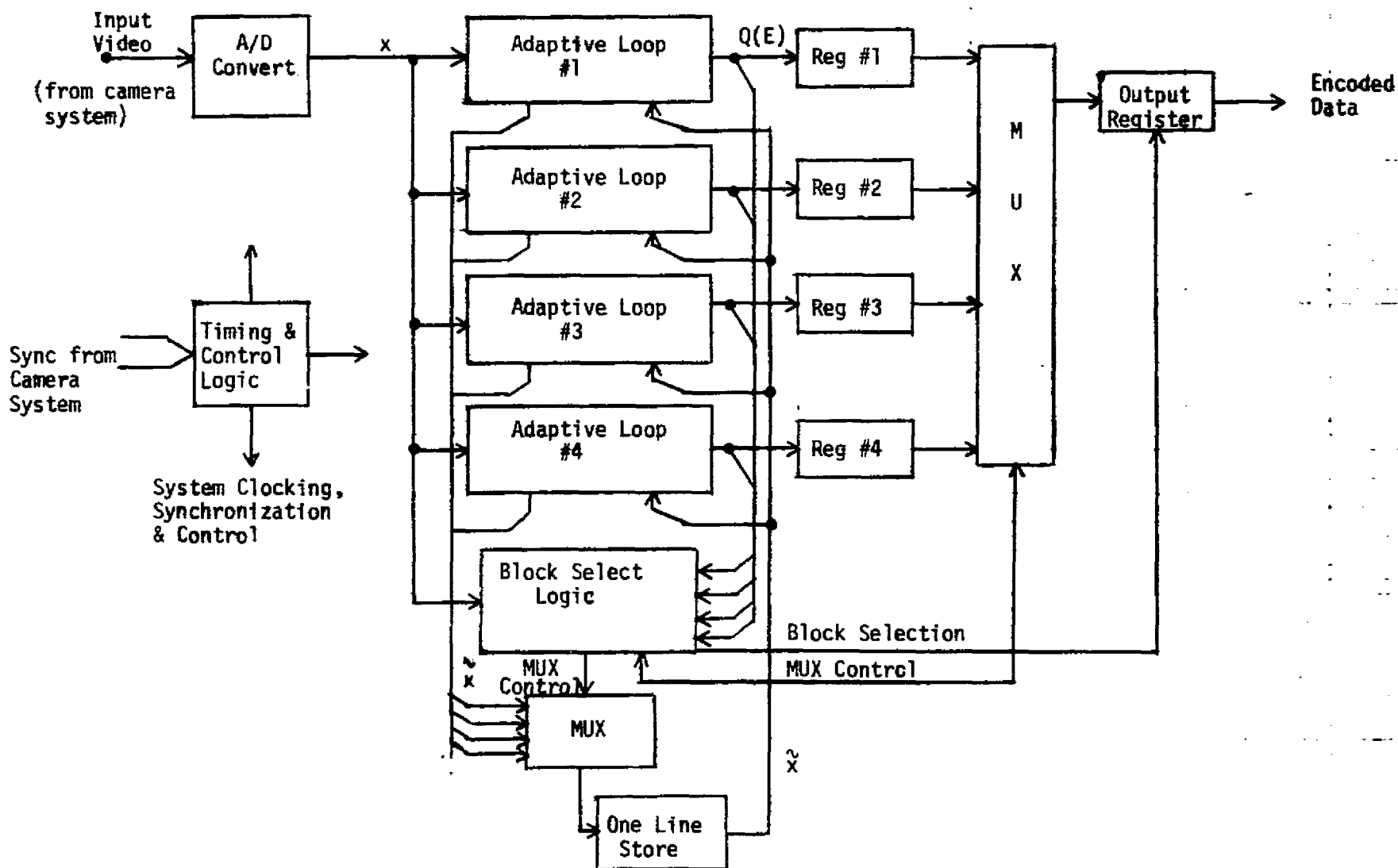


Figure 4-15. Multiple Loop Adaptive 2D-DPCM Encoder

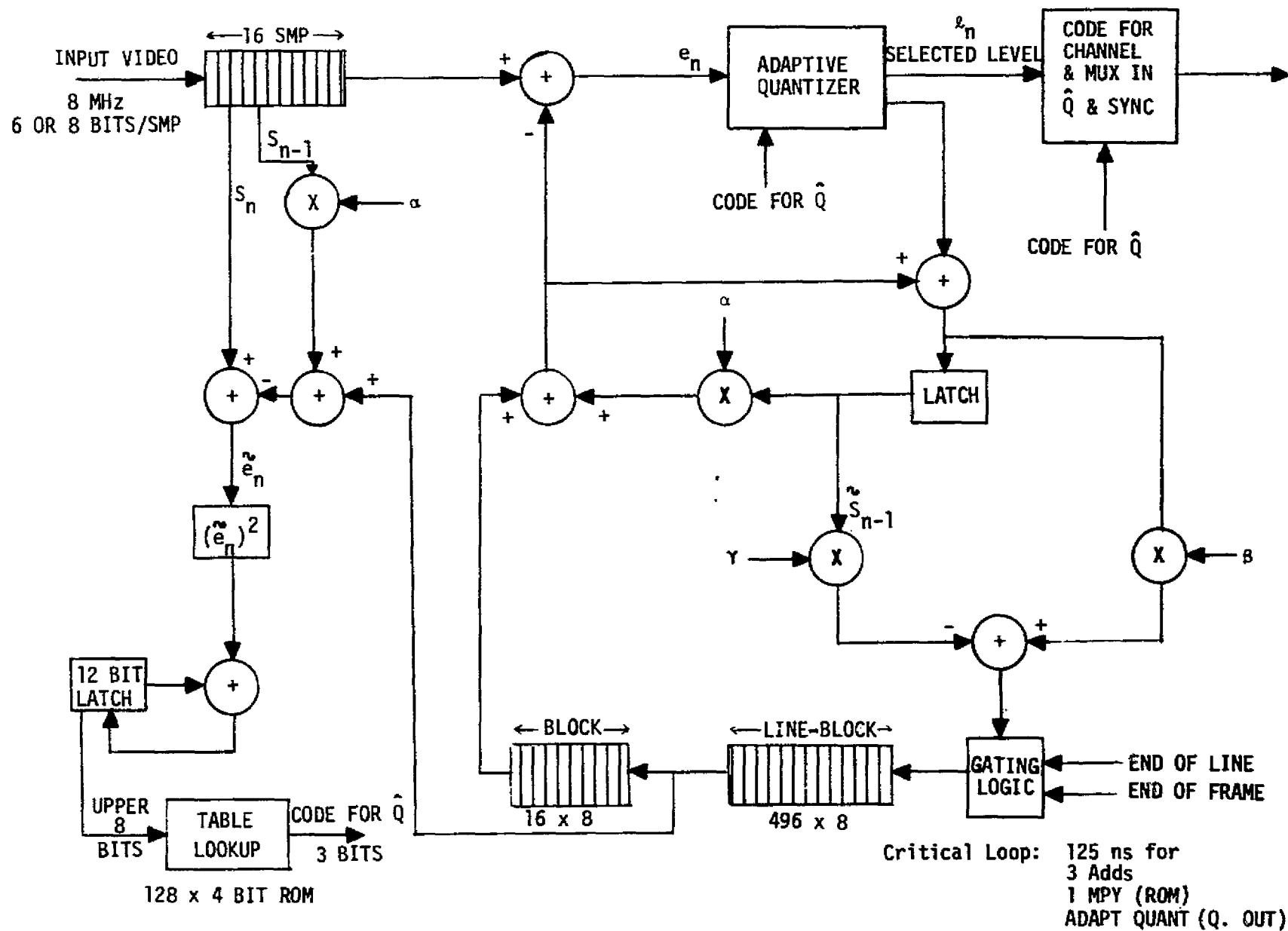


Figure 4-16. Single Loop Block Adaptive 2D-DPCM Encoder

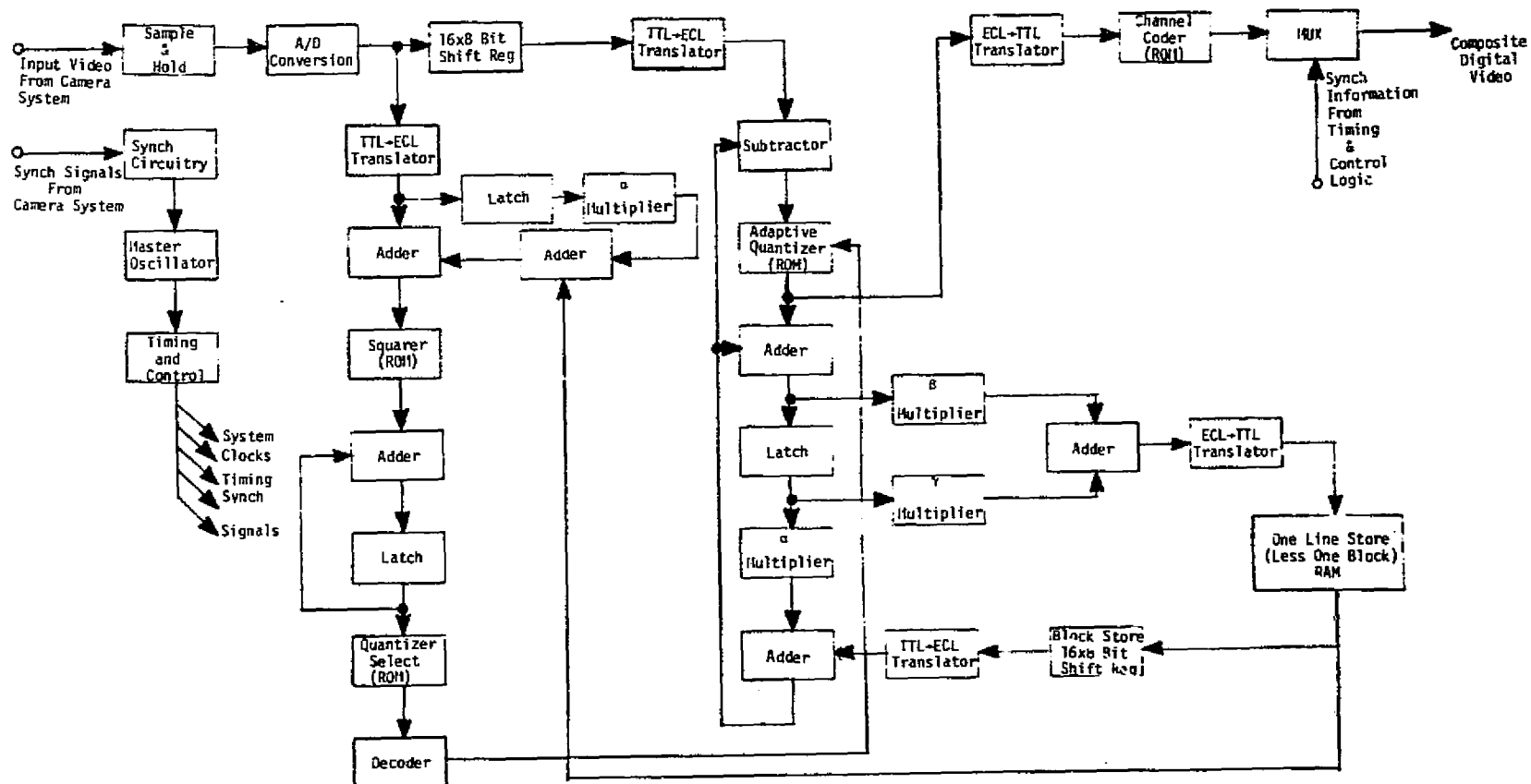


Figure 4-17. Mechanization of the Single Loop Block Adaptive 2D-DPCM Encoder

#### 4.3.6.3 Hybrid Hadamard/DPCM System Complexity

The hybrid compressor utilizes a one-dimensional Hadamard transform in the vertical (line to line) axis, and a one-dimensional horizontal (adjacent samples along a line) DPCM compressor.

The Hadamard transform is performed on a subpicture comprised of four adjacent vertical samples. This requires that four lines of video be stored, and that vertically adjacent samples be presented simultaneously to the Hadamard transform processing logic array. Figure 4-18 depicts this configuration. The seeming disadvantage of having to store four lines of information is in reality an advantage. By providing storage for an additional four lines of video, the Hadamard transform processing and subsequent DPCM processing can be performed at 1/4 the pixel rate. The use of a pipeline Hadamard transform and parallel DPCM processing loops permits the usage of low power Schottky logic elements. In turn, this provides a significant reduction in system power consumption (comparable to the non-adaptive 2D DPCM system).

Figure 4-19 illustrates a mechanization of the hybrid system. Input video information from the camera system is digitized at an 8 MHz rate. Internal processor system clocks and synch signals are derived from the camera system synch signals. The encoded video samples are demultiplexed into the four line storage elements. Each line of storage is sufficient for 512 encoded samples. When the four line stores are filled, the incoming video is demultiplexed into the other four line store while the previously filled store outputs data, four lines at a time, at one quarter the video line rate. The Memory Multiplexer operates in conjunction with the line demultiplexer, distributing data to the transform unit.

The memory contents are transferred to the Hadamard transform processing array four adjacent samples at a time. This processor performs the following algorithm:

$$\begin{bmatrix} F_2(0) \\ F_2(1) \\ F_2(2) \\ F_2(3) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{bmatrix} \times \begin{bmatrix} F_0(0) \\ F_0(1) \\ F_0(2) \\ F_0(3) \end{bmatrix}$$

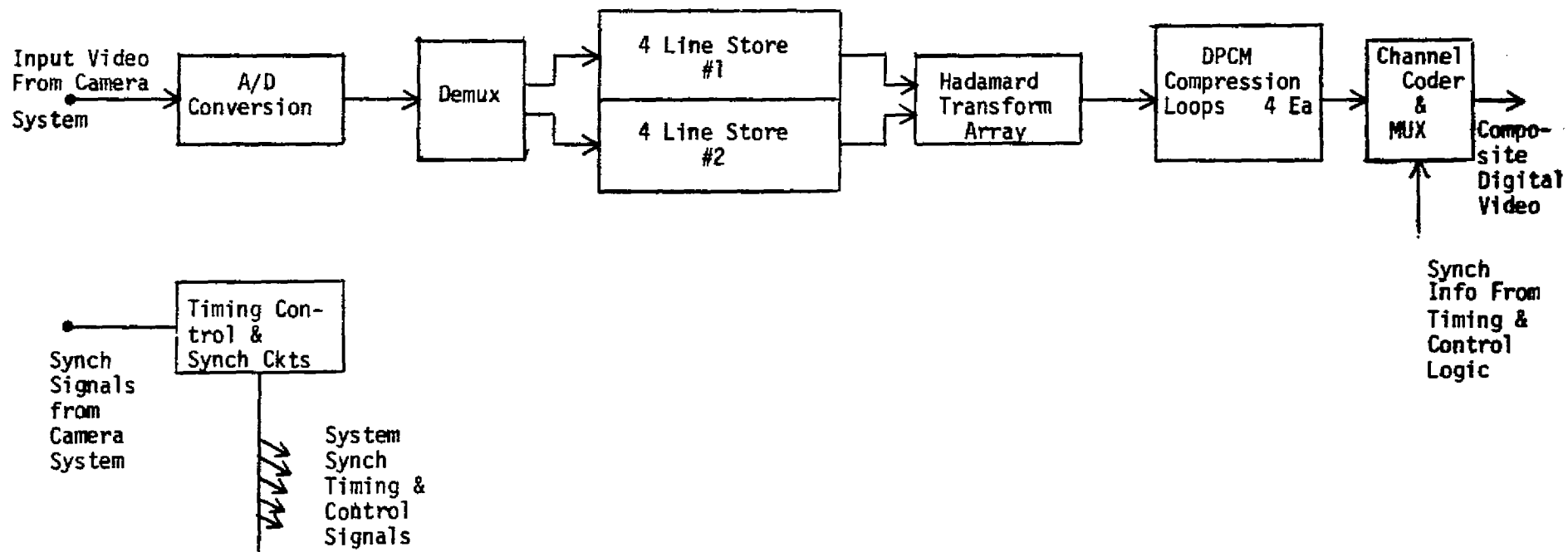


Figure 4-18. System Block Diagram of Hybrid Encoder

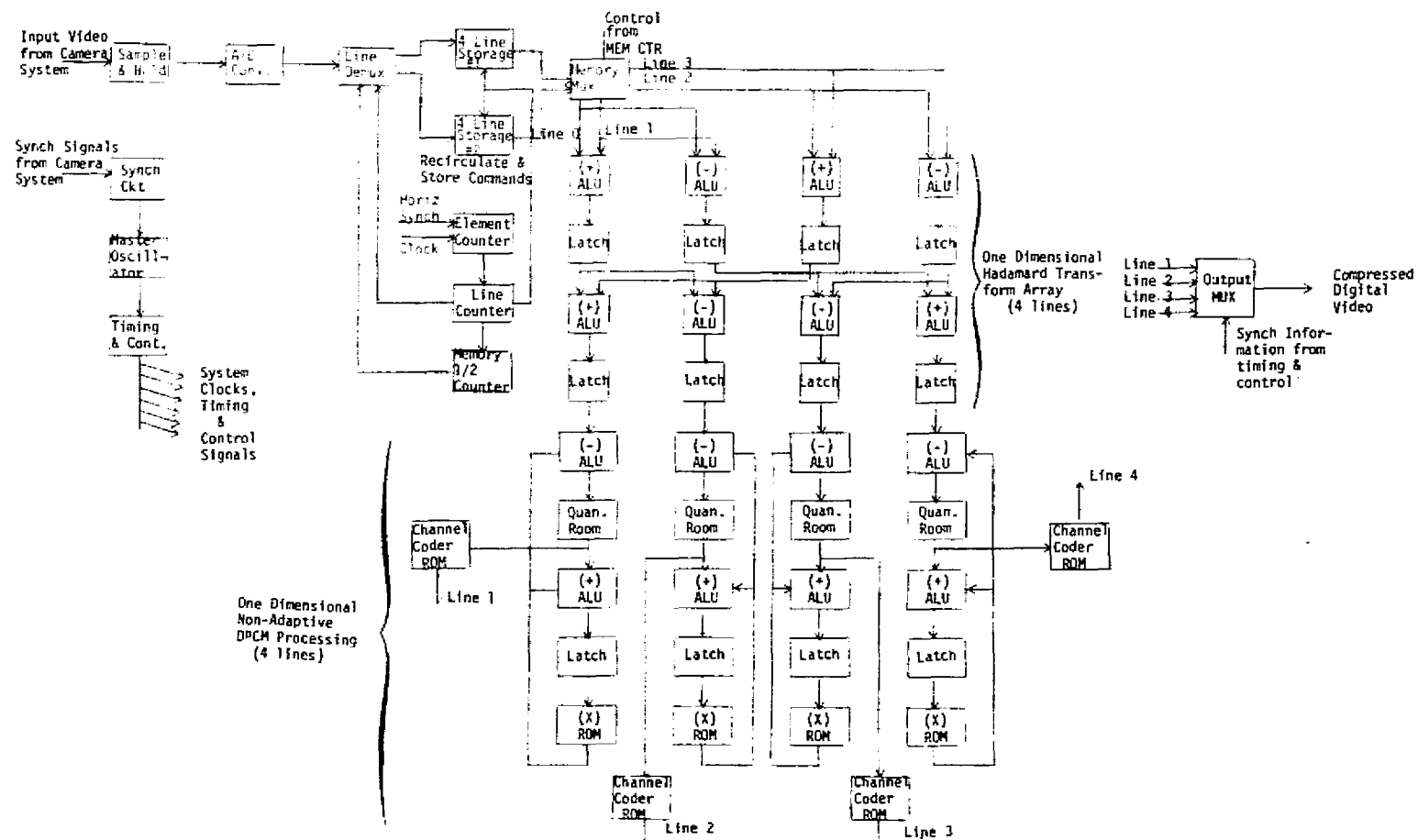
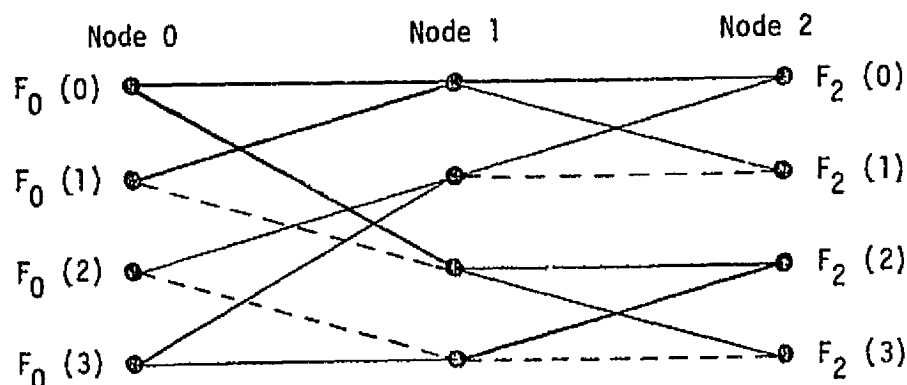


Figure 4-19. Implementation of the Hybrid Hadamard/DPCM Encoder

with the processing proceeding in accordance with the following flow:



$$\text{where } F_2(0) = F_0(0) + F_0(1) + F_0(2) + F_0(3)$$

$$F_2(1) = F_0(0) + F_0(1) - F_0(2) - F_0(3)$$

$$F_2(2) = F_0(0) - F_0(1) - F_0(2) + F_0(3)$$

$$F_2(3) = F_0(0) - F_0(1) - F_0(2) - F_0(3)$$

The pipelined Hadamard processor outputs are fed to four non-adaptive DPCM compressor loops, one per line. Subsequent to the parallel DPCM processing, the quantized outputs are multiplexed along with the appropriate (line/field) synch and formatted for transmission in the Output MUX.

#### 4.3.6.4 Comparison of Hardware Complexity

Table 4-4 presents a comparison of the characteristics of each of these systems. The parameters chosen for comparison are IC count (related to system size and weight), and power consumption. Since the compressor loops consume the most power, the multiple Quantizer-Single Loop Encoder compares favorably with the baseline Non-Adaptive system. It has eight times the flexibility with only a 79% increase in power consumption, and a 58% increase in IC count. It is felt that a more detailed sizing could further reduce these differences.

Table 4-4. Hardware Complexity Comparison of the Various Bandwidth Compression Approaches

IC Count	Power Dissipation	Non-Adaptive 2D DPCM Encoder	Adaptive 2D DPCM Encoder (Multiple Loop)	Adaptive 2D DPCM Encoder (Single Loop)	Hybrid Encoder (1D Hadamard/1D DPCM)
A/D Converter		3 Modules/1W	3 Modules/1W	3 Modules/1W	3 Modules/1W
Adaptive Predictor/Block Select Logic		-----/-----	34 IC/8.9W	23 IC/11.27W	-----
Compressor Loop(s)		26 IC/12.4W	224 IC/70W	42 IC/20W	76 IC/10.24W
Line Store		6 IC/1.56W	20 IC/1.6W	16 IC/3.2W	55 IC/5.15W
Timing and Control		20 IC/6.3W	40 IC/12.8W	20 IC/6.3W	20 IC/6.3W
Miscellaneous		30 IC/5.6W	35 IC/5.6W	30 IC/5.6W	30 IC/5.6W
TOTALS		85 IC/26.9W	356 IC/99.9W	134 IC/47.4W	184 IC/28.3W
NOTES		Baseline configuration requires ECL for compression loop. Worst case loop completion time = 116 nsec.	Configuration employs multiple compression loops and a single block selection logic. ECL logic required within the compression loops.	Configuration requires ECL for both predictor and compression loops. Adaptive quantizer comprising 8 individual quantizers requires 16 ECL ROMs. Partitioned (496 + 16 bits) line memory requires 40 ICs.	Configuration allows usage of low power Schottky components. Compressor loop figures include both Hadamard transform logic, and 4 DPCM loops. Eight lines of multiplexed buffer storage are provided within the line store.

#### 4.3.7 Recommended Field-Sequential Color Data Compression Approach

Analysis of the Field-Sequential data along with the weight and power sizing of the encoder lead to an approach that consists of using the green (G) field instead of the illuminance and generating the chromaticity signals by subtracting G from the red (R) and the blue (B) fields. This approach is fruitful if the chrominance signals contain less energy and possess a smaller bandwidth than the original fields. Then the chrominance signals can be subsampled by taking every other sample and encoded using a coarser quantization; thus resulting in a further bandwidth compression. Table 4-5 shows the statistics of the G and two chromaticity signals for three typical fields of the field sequential data. Figure 4-20 shows the power spectra of the green as well as the chromaticity signals. These results indicate that the chrominance signals indeed possess a smaller energy and a lower bandwidth than the original fields.

The above processing of the field sequential data results in some reduction in its bandwidth. This is due to subsampling of the R-G and B-G fields. A 2 to 1 subsampling of R-G and B-G results in a total bandwidth compression ratio of 1.5 to 1. To achieve additional bandwidth compression, the G, R-G, and B-G fields must be encoded. Four candidate bandwidth compression techniques were presented in previous sections. The performance of the candidate techniques are shown on Figure 4-21. The two adaptive DPCM systems have essentially identical performances. The performance of the hybrid encoder, on the other hand, is almost the same as the performance of the non-adaptive DPCM encoder. The difference in the performance of the adaptive and non-adaptive DPCM system is fairly small at 3 bits per sample. At 2 bits per sample, the difference is about 3 dB in Signal-to-Noise ratio and may be significant for some applications. On the other hand, the complexity of the adaptive DPCM encoder (Table 4-4) is much greater than the complexity of the non-adaptive DPCM encoder. For this reason and the fact that the lighting will be well controlled in the Shuttle, the non-adaptive DPCM encoder is selected over the adaptive DPCM system. The hybrid encoder was rejected because it requires more than twice the parts count of the non-adaptive DPCM encoder.

Table 4-5. Statistics of the Field-Sequential G, R-G, and B-G Fields

Fields	Minimum	Maximum	Average	Standard Deviation
G	0.0	255	117.05	51.77
R-G	-101	60	8.03	12.48
B-G	-88	77	1.80	9.30

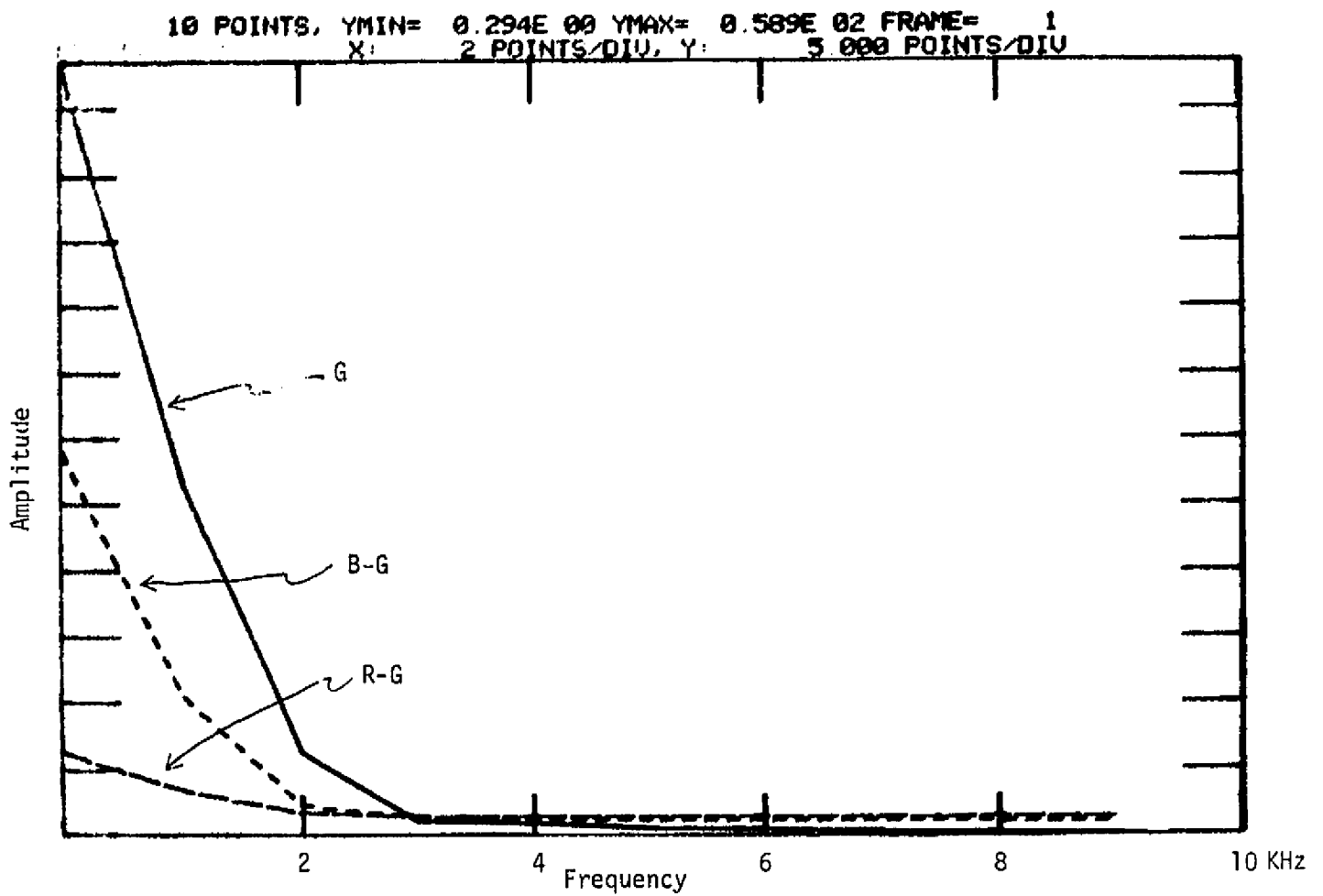


Figure 4-20. Relative Power Spectra of G and R-G, B-G Fields

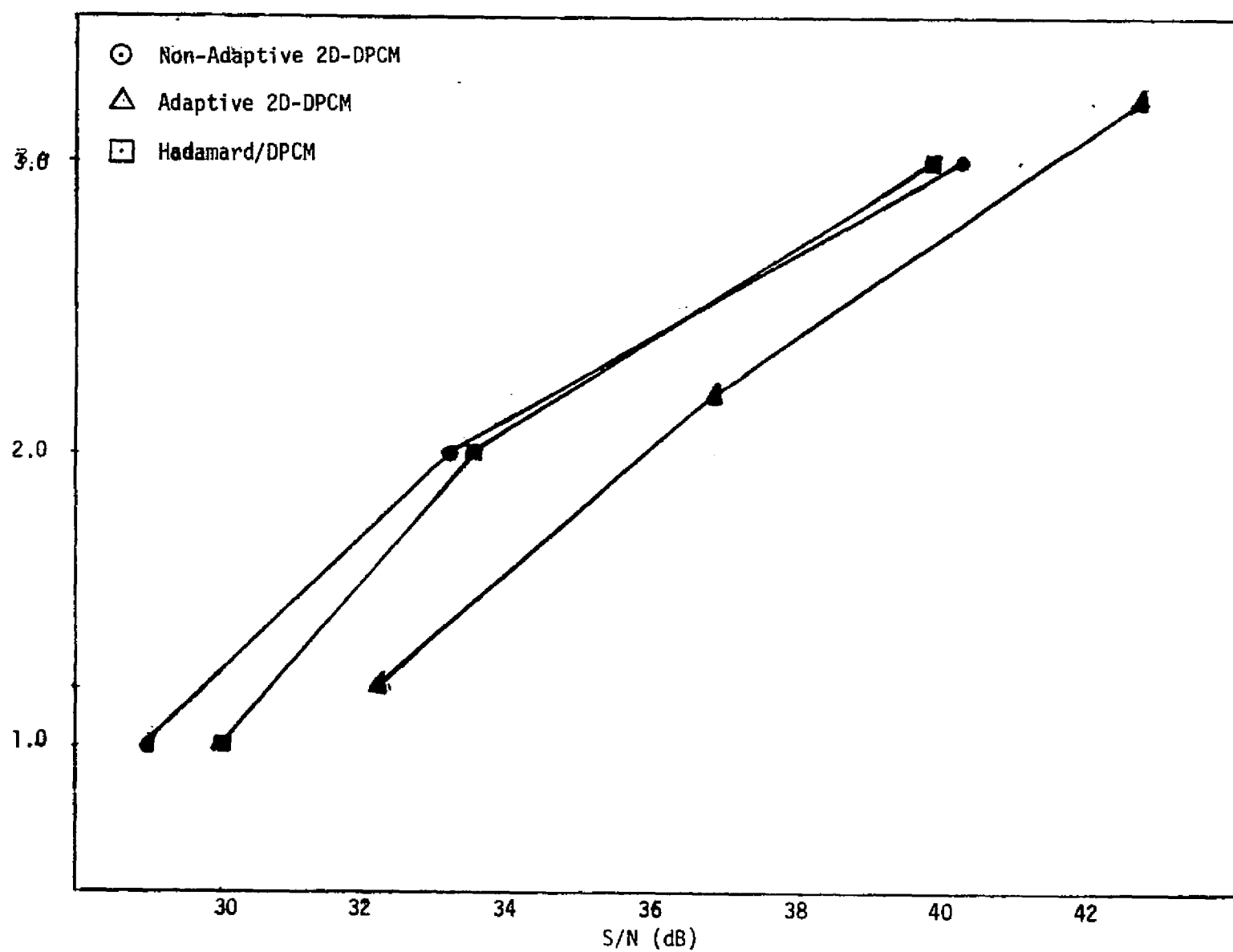


Figure 4-21. Performance of the Candidate Coding Techniques in Terms of Signal-to-Noise Ratio

#### 4.3.7.1 Bandwidth Compression Procedure

A block diagram of the proposed bandwidth compression technique for the Field-Sequential color TV is shown on Figure 4-22. The system starts its operation upon the receipt of the green field. It is encoded using a 2D-DPCM loop and is transmitted using 3 bits per sample. The green field is also filtered by a 3-point hanning filter, subsampled and stored in the field memory. This requires storing only 256 samples per line. Next the R field is filtered, subsampled and combined with the G field to generate R-G for each line. R-G is encoded using a DPCM loop with a 4 level quantizer. Finally, the same procedure is also used to generate and encode the B-G field. Since G is encoded in full resolution at 3 bits per sample, but R-G and B-G are encoded at 2 bits per sample with reduced resolution, rate buffering at the output of the encoder is required.

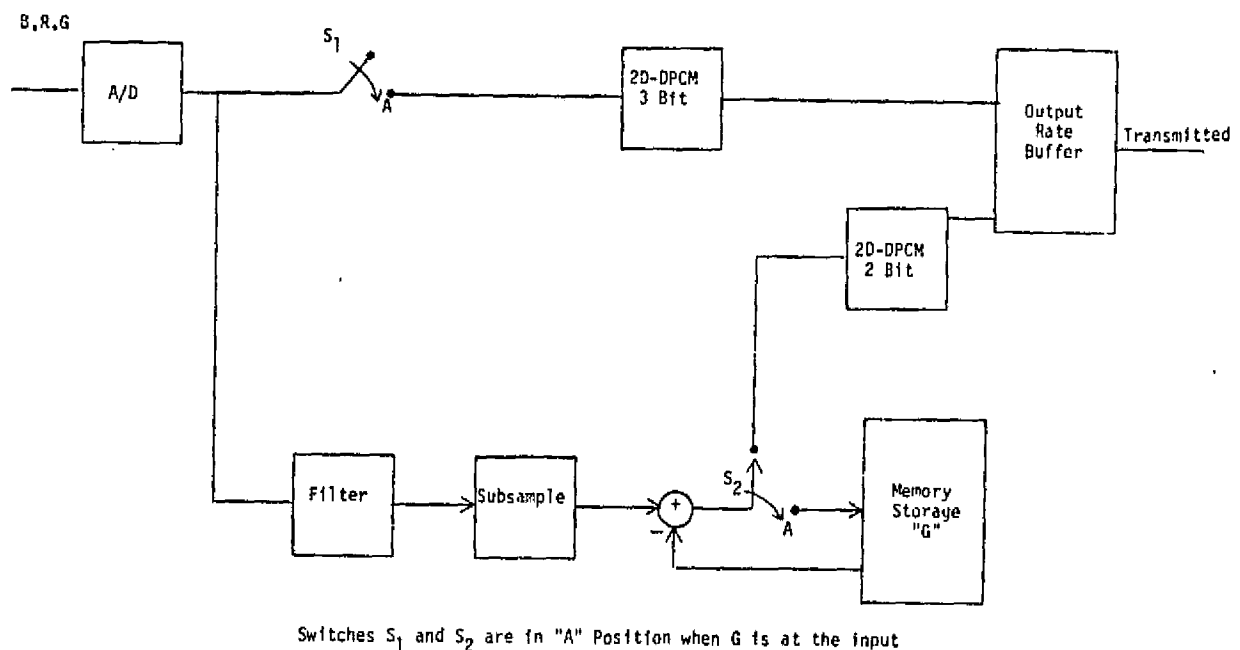


Figure 4-22. Block Diagram of the Proposed Bandwidth Compression Technique for Field-Sequential Color TV

#### 4.3.7.2 Field Memory and Buffering Requirements

Figure 4-23 illustrates the operation of the pre-compression green field memory. Input video data from the A/D converter (8 MHz sampling rate) is applied to the Green Field Select Logic. Green field data is passed via the output select logic to the video compressor circuitry. Also, the green field, as well as red and blue fields, are subsampled by taking every other sample in the subsampling logic. As a green field emerges from the subsampling logic, it is loaded into the serial green field memory by means of the recirculate switch. This switch is activated by the recirculate logic; thus data is returned to the memory during the next two successive fields (red and blue). This insures that spatially related video samples differing only in successive field numbers are subtracted from each other, and this difference is fed to the DPCM compressor circuitry. During the initial memory load time, the subtractor output is disabled, and the green field data is fed to the compression logic. Due to the serial nature of the data, 16K CCD (charge coupled device) shift registers have been chosen for implementation of the serial green field memory.

The proposed Field-Sequential Color TV compression system requires a post compression rate buffer memory. This requirement arises from the unequal sampling rates of the "Green" field and the R-G, B-G fields. In addition, the green field is encoded at 3 bits/sample while the R-G and B-G fields are encoded at 2 bits/sample. Therefore, the output rate changes from 23.6 Mb/s for the green field to 7.8 Mb/s for the remaining two fields. To maintain a constant output rate, a buffer memory is required to smooth the output rate to 13.1<sup>\*</sup> Mb/s. Figure 4-23 shows the functional block diagram of the proposed rate buffer memory mechanization. Because of the differing input and output data rates involved, a random access memory (RAM) has been chosen. The output data from the video compressor is input to the demultiplexer for double buffering into the RAM memory. Double buffering is required so that no interruption of the input data will occur while memory loading takes place. Thus each sample is shifted into the buffer register (a sample at a time) and loaded (rewritten) into the memory, 12 bits at a time. To prevent data loss, two buffer registers (double buffering) are required, one holding data for load, the other accumulating data. This technique slows the input and output memory data rates to where read/write collision<sup>\*\*</sup> can be avoided by simple priority logic. Table 4-6 lists the number of integrated circuits and required power for the operation of the field memory and rate-buffering

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\*The actual rate will be slightly higher due to inclusion of synchronizing signals.

\*\*Read/write collision may be described as attempts to write into the memory at one location (address) simultaneous with an attempt to read from the memory at another location.

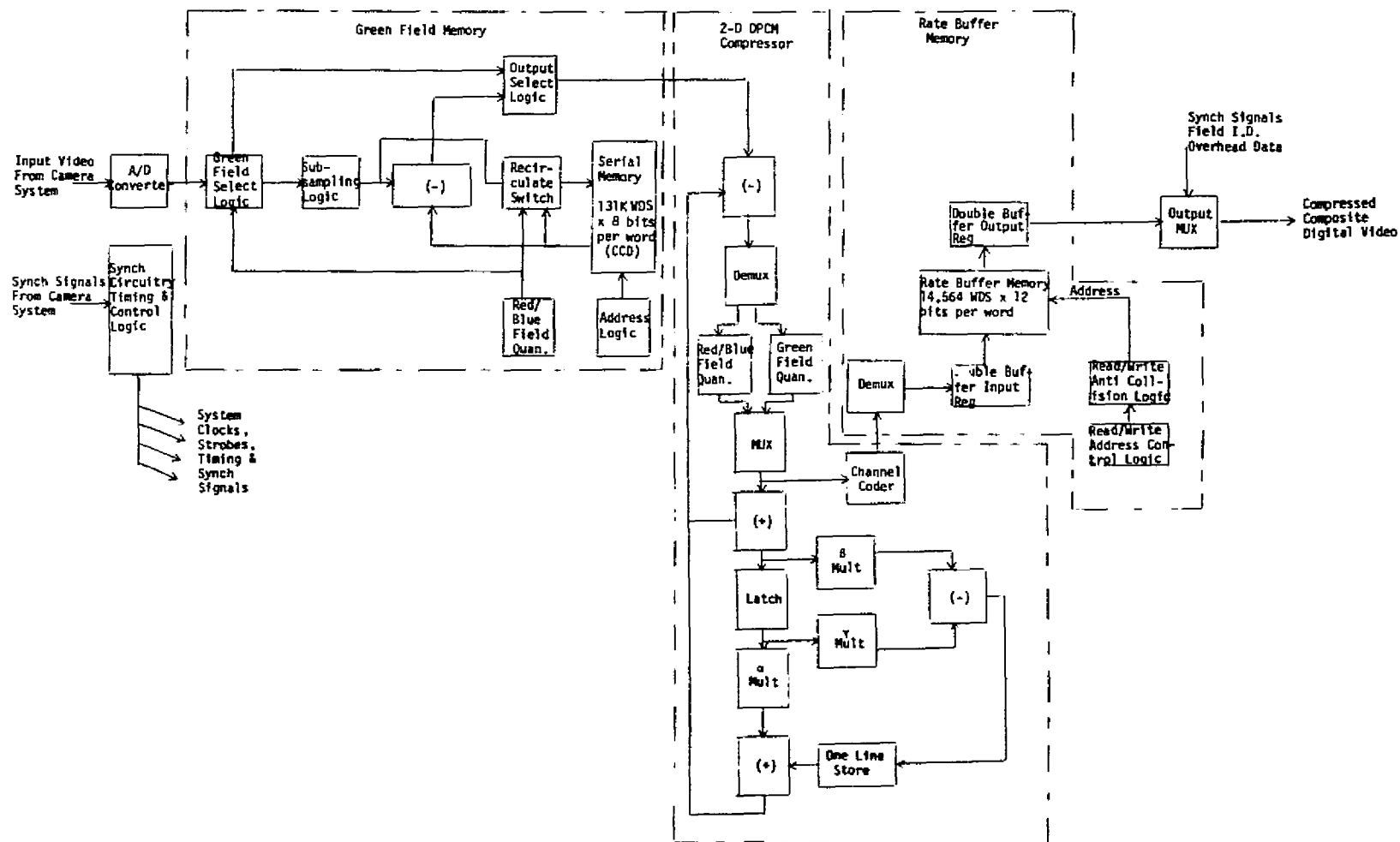


Figure 4-23. Functional Block Diagram of the Proposed Bandwidth Compression Technique for Field-Sequential Color TV

logic. The double buffer slows the memory input rate to a point where in the event of a collision, there is sufficient time to allow a data read before the data write. This anti-collision control is provided by the Read/Write combiner and anti-collision logic. Data read from the memory is stored in the output data buffer register, and shifted to the transmission link. Read, Write and Refresh address control are provided by the appropriate counters.

Table 4-6. Field-Memory and Rate-Buffering Circuitry

Memory	IC Count	Power Consumption
Green Field	56	20.5 Watts
Rate Buffer	207 or 47*	12.6 or 21.4* Watts

\* Rate Buffer Memory comprises 171 1K x 1 CMOS/SOS RAM memory elements. The same Rate Buffer Memory may be implemented using 16K RAMS with a parts decrease and power increase.

The total hardware complexity of the non-adaptive 2D-DPCM Field-Sequential Color TV bandwidth compression system is summarized in Table 4-7. For a modest increase in power consumption (8.5 watts), the parts count can be reduced by almost 50 percent.

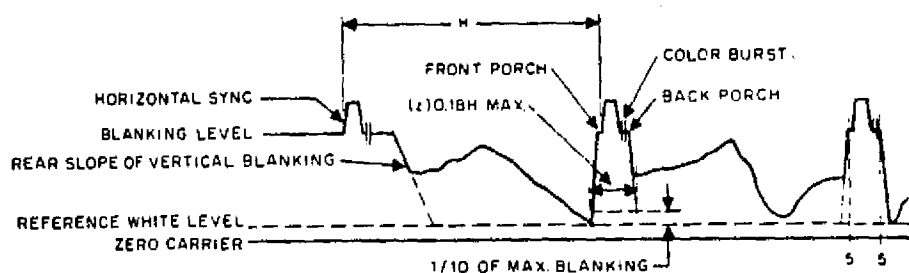
Table 4-7. Total Bandwidth Compression hardware Complexity

Rate Buffer Memory	IC Count	Power Consumption
1K RAMS	348	60.0
16K RAMS	188	68.5

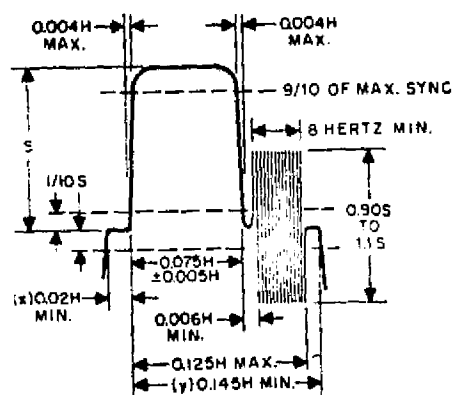
#### 4.4 BANDWIDTH COMPRESSION OF NTSC COLOR TV

We propose a modification of the standard NTSC color TV system so that the analog illuminance (Y) and chromaticity signals (I, Q) are available in an unmodulated form. In the absence of such a modification, a comb filter is required to demodulate these signals. The proposed bandwidth compression technique for the NTSC Color TV uses a 2D-DPCM loop.

In the analog transmission of I and Q signals, they are low-pass filtered and multiplexed with the illuminance signals as shown in Figure 4-24. This technique is practical since human vision is very insensitive to high frequency components of I and Q signals. Taking advantage of this property, we also propose low-pass filtering of the I and Q signals. The passbands of these filters are about one fifth of the illuminance signal. Maintaining a spatial resolution of 512 samples per line gives a spatial resolution of about 100 samples per line for I and Q signals. A further bandwidth compression can be achieved by alternating the transmission of the I and Q signals with each line of the illuminance signal. The receiver then restores the missing color component for each line by interpolating between the transmitted components for the previous and the future lines. The performance of such a system was evaluated at Bell Laboratories for the Color Picturephone.<sup>(30)</sup> There was no color degradation as a result of alternate transmission of the chromaticity signals.



(A) Line Structure



(B) Detail Between 5-5 in (A)

Figure 4-24. NTSC Color Composite Signal Waveform

A block diagram of the proposed encoder is shown on Figure 4-25. The illuminance signal is sampled at a rate of 7.8 MBPS and is encoded by a 2D-DPCM system at 3 bits per sample. The sampling and transmission of the illuminance signal takes place during the active period of the line scan. During the period of blanking, flyback and the interval which is normally used for analog transmission of the modulated color signal, we propose to transmit either I or the Q signals. The corresponding time intervals for commercial NTSC Color TV are shown in Figure 4-26. This arrangement gives sufficient time for transmission of 100 chrominance samples in the non-active interval. Both illuminance and the chromaticity components can use the same 2D-DPCM encoder if additional memories are provided to store 100 samples of I and 100 samples of the Q signal for the use in the DPCM predictor. This additional memory and the memory required to delay I or Q for the active duration of a line scan are the only components that need to be added to the 2D-DPCM encoder. The encoder sizing is summarized in Table 4-8.

The performance of this system would be very similar to the performance of the proposed system for Field-Sequential Color TV since they both use the same 2D-DPCM encoder for the bandwidth compression of the illuminance signal. The bandwidth of this system, however, is higher. To maintain the same spatial resolution as that of Field-Sequential Color TV signal requires 28 Mbit per second.

#### 4.5 RECOMMENDED BANDWIDTH COMPRESSION APPROACH FOR THE SLOW-SCAN UPLINK

NASA is considering a slow-scan high resolution system for transmitting pictorial data from the ground station to the Shuttle. Various modes of operation as well as the characteristics of the imagery under consideration for this system were discussed in Section 4.1.2. For this application we require distortion free bandwidth compression techniques that require a simple decoder. One such technique with desirable characteristics is the two-dimensional HCK code (see Section 3.3.2). The proposed facsimile system is described in the following sections.

##### 4.5.1 Algorithm Description

The two-dimensional HCK code operates on blocks of M by N samples. For a block consisting of white samples, a 1-bit code word "0" is used. For a block that consists of at least one black sample an  $(M \times N + 1)$  bit code word is used, where the first bit is "1" and the next  $M \times N$  bits are the binary pattern of the  $M \times N$  pel block. The technique also applies to multi-level imagery by again using "0" for a block with all white samples and using "1" followed by  $M \times N \times \log_2 m$  bits for the blocks with at least one non-white sample. Here  $m$  is the number of grey levels per sample and it is assumed that  $\log_2 m$  is an integer.

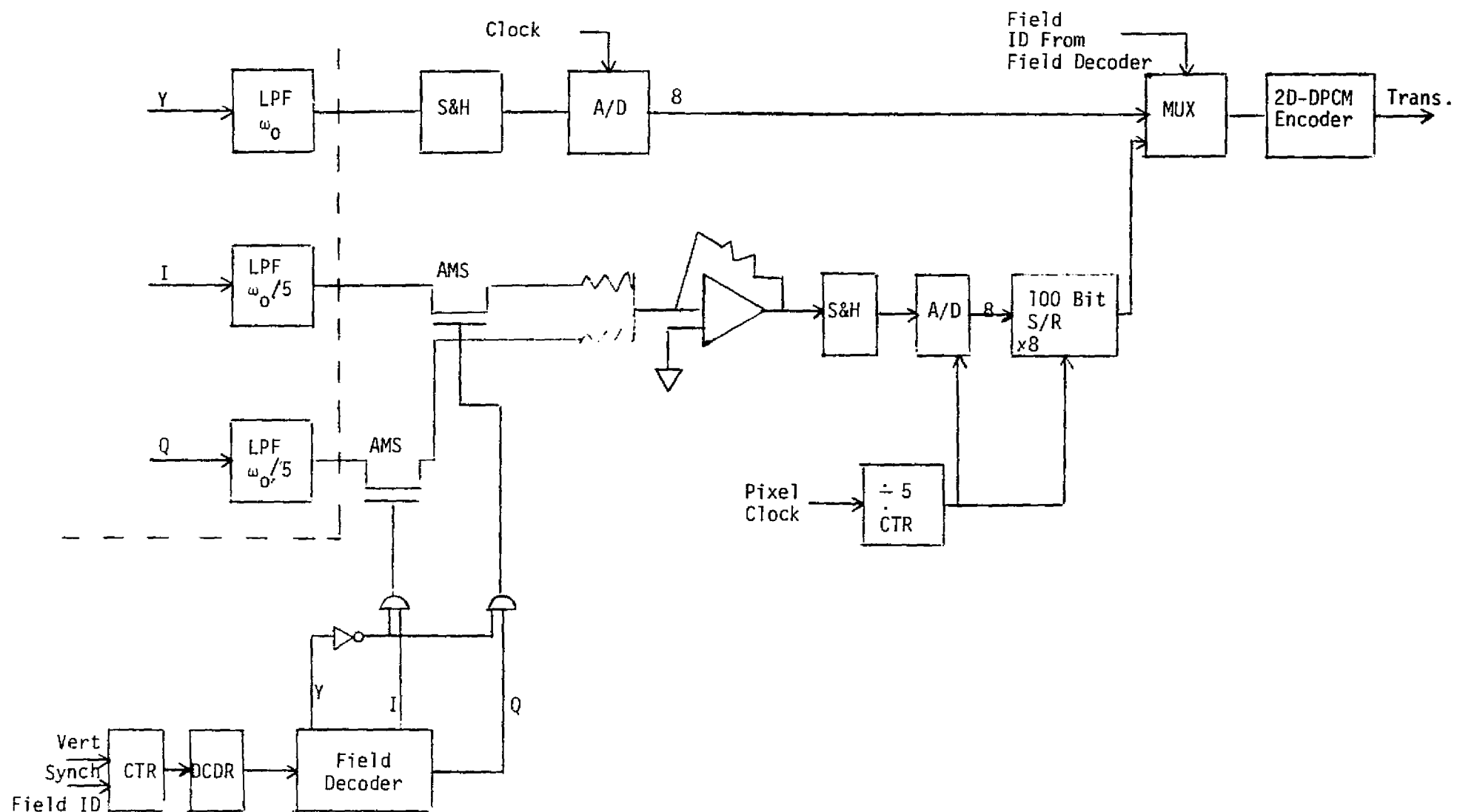


Figure 4-25. Block Diagram of Proposed Bandwidth Compression System for NTSC Color TV

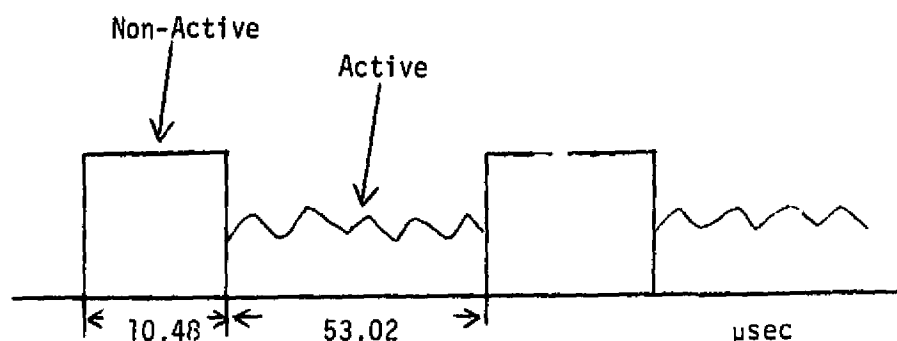


Figure 4-26. Active and Nonactive Portion of the Scan Line

Table 4-8. Encoder Sizing for the NTSC Color TV System\*

Technique	Power (Watts)	No. of Integrated Circuits	Bandwidth (Mbps)
NTSC Color TV	30.5	108	28

\*It does not include the low pass filters in Figure 4-25

We have simulated this technique for binary data and blocks of 3 x 3 and 4 x 4 samples and the results are shown in Table 4-9. Compression ratios achieved vary between 5:1 and approximately 1:1. The "Galaxie" picture produced a slight bandwidth expansion because the background of the image is black. If the encoding convention for black and white was reversed, then a reasonable compression ratio could be achieved.

#### 4.5.2 Implementation Complexity

Figure 4-27 shows the functional block diagram of the 1 bit per sample Uplink Decoder. This system receives a serial data stream at the rate of 144 K bits per second. The received data represents a block of 16 pixels (4 rows and 4 columns) and is preceded by a one bit preamble. If the preamble bit is a logic 1, the value of the 16 pixels within the block follows. If the preamble bit is a logic 0, no further data for that block will be received. Instead, the decoder will provide 16 logic 1's. The decoder system performs an additional function of converting the data from block format to line format, for use within a display system. The design described herein is sufficiently flexible and modular as to accommodate any number of bits per pixel with only minor changes in addressing logic, formatting logic and additional memory.

Throughout the following discussion, the one bit per system will be considered. The six bit per pixel system will be mentioned wherever it significantly differs from the one bit per pixel system. Figure 4-28 shows the block diagram of the decoder for the six bits per sample configuration.

Table 4-9. Performance of 2-Dimensional HCK Codes on Binary Images

Scenes	350 lines per inch (1024 x 1024)		120 lines per inch (341 x 341)	
	Block size 3 x 3 (bits/pel)	Block size 4 x 4 (bits/pel)	Block size 3 x 3 (bits/pel)	Block size 4 x 4 (bits/pel)
Prints (70 samples/ line)	0.305	0.296	0.451	0.442
Brake Control Pedals	0.406	0.385	0.493	0.488
Skylab Maximum Zoom Map	0.395	0.374	0.494	0.498
Galaxie	1.090	1.045	1.095	1.052
Circuit Diagram	0.230	0.199	0.298	0.301
Skylab Minimum Zoom Map	0.518	0.498	0.593	0.604
Average Compres- sion Ratio	2.58	2.77	2.04	2.04

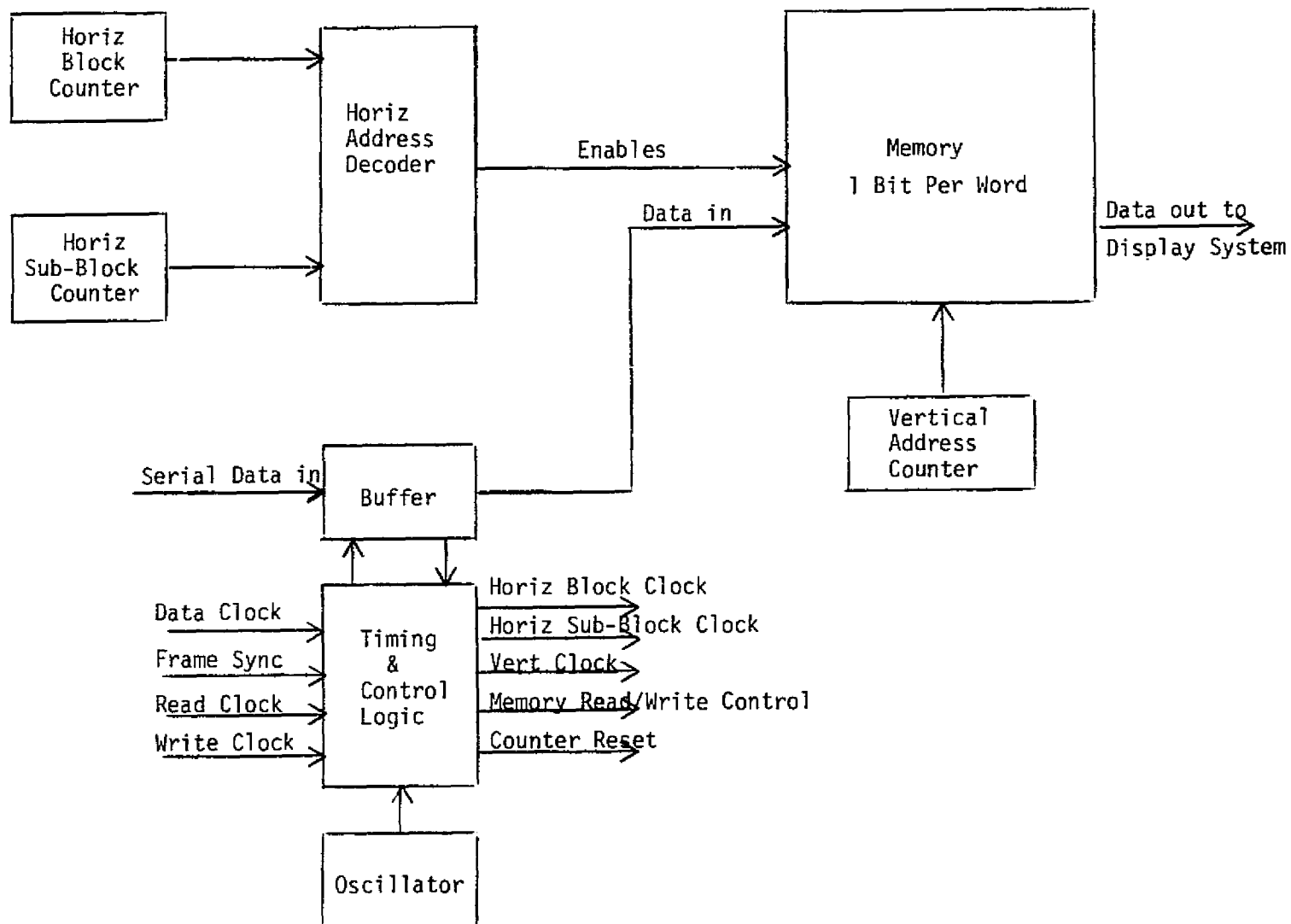


Figure 4-27. Functional Block Diagram — Uplink Decoder System -- 1 Bit Per Pixel

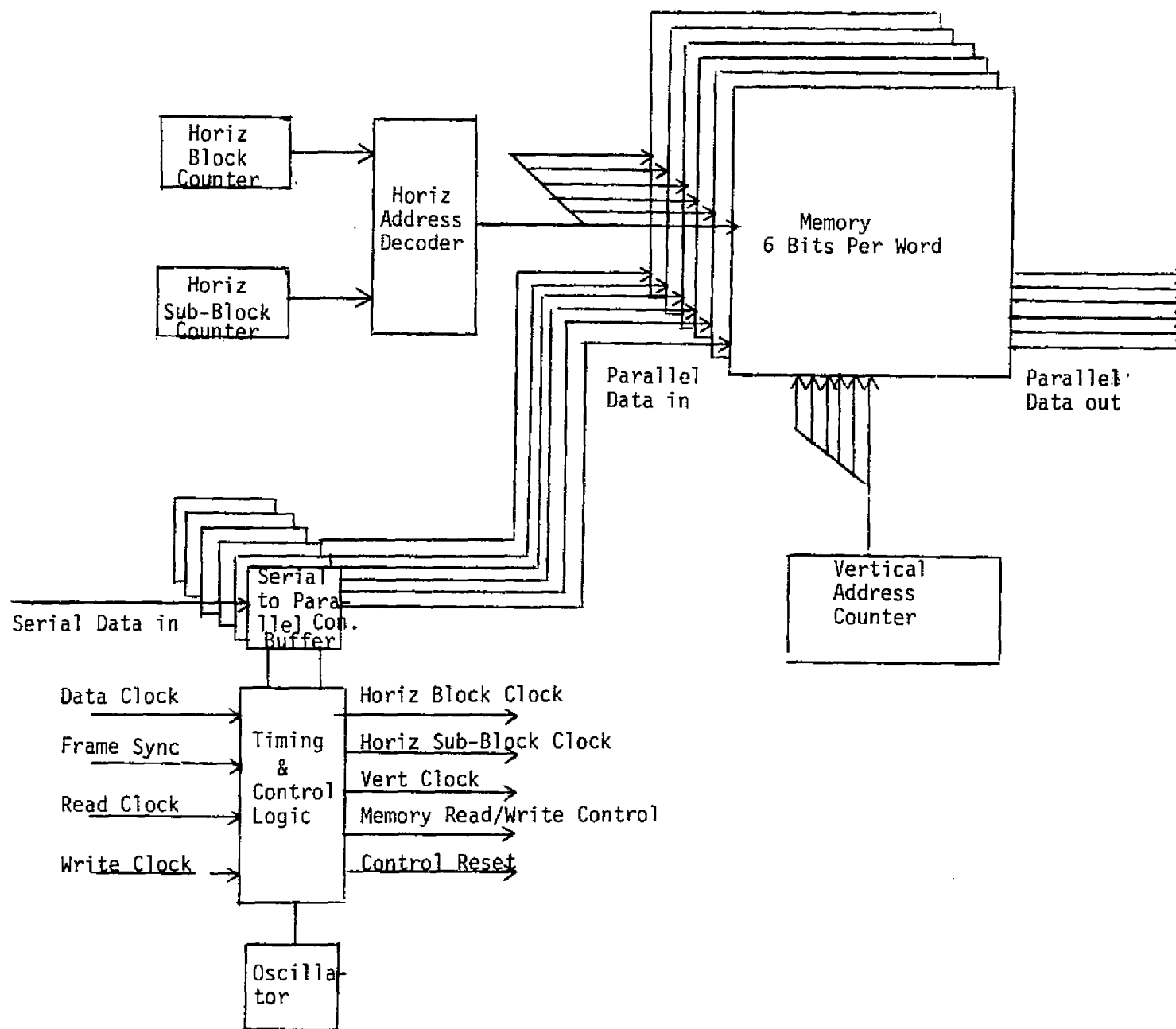


Figure 4-28. Functional Block Diagram of the Uplink Decoder - 6 Bits Per Pixel

Serial data, a data clock, and frame sync are input to the system. The Timing and Control Unit interrogates the data to determine the state of the preamble bit. If the preamble bit is determined to be a logic 1, the buffer is enabled to pass the data through the buffer gate. Simultaneously in synchronism with the Data Clock, the Memory Address counters are advanced, and write commands are supplied to the memory to store the next 16 bits. If the preamble bit is decoded as logic zero, 16 ones will be loaded into the memory. The loading of these prestored logic 1's will be accomplished using an internal oscillator running at slightly more than 16 times the Data Clock Rate. This higher rate is required so that the block will be loaded prior to the next input data bit. The six bit per pixel system differs from the foregoing discussion in that prior to memory load, the data stream will be serial to parallel converted using a six bit serial in/parallel out shift register. Each bit of each sample will be loaded into a memory chip at the same address, with six chips loaded simultaneously.

Format conversion is accomplished by the addressing logic. It is assumed that the data is supplied in column serial format. That is, the first column top pixel sequentially through the bottom pixel, the next column sequentially top pixel through bottom pixel, etc. The memory is organized as 4 each (actually 8 each in a double buffered configuration) 1024 word Random Access Memories (RAM) of one bit per word format. Each RAM represents one complete row of data. Thus the data will be written sequentially into the memories at a given address (column) while each RAM is sequentially enabled (row). When all four rows have been filled, the column (vertical) address will be advanced. When 1024 locations within each row have been filled, the read clock will be energized and the data read sequentially row by row to the display device. The memory is provided as a double buffered store so that reading progresses from one memory array while writing proceeds into the other. In this manner, by writing in vertically and reading out horizontally the row/column conversion is accomplished.

For the six bit/sample system, memory control is similar. The major difference is that the data is written into, and read from six RAMS simultaneously.

Table 4-10 shows the estimated parts count (IC's) and power consumption for both the one bit/sample and six bit/sample systems.

Table 4-10. Hardware Complexity of the Proposed Bandwidth Compression Technique for the Slow-Scan System

Systems	No. of Integrated Circuits	Power Consumption (Watts)
One Bit/Sample System	102	18.7
Six Bits/Sample System	118	18.9

Note: Design assumes use of CMOS-SOS RAM organized as 1024 x 1 RAM.

## 5. CONCLUSIONS AND RECOMMENDATIONS

This section discussed the major conclusions and recommendations of the study.

### 5.1 CONCLUSIONS

We have analyzed the feasibility of compressing the bandwidth of Shuttle TV systems which include the Field-Sequential and NTSC Color TV for downlink transmission and a slow-scan high resolution TV system for uplink transmission. The conclusions are that digital bandwidth compression techniques can be utilized to reduce the bandwidth of the Shuttle TV systems. The recommended techniques approach the imposed weight power goals and produce high fidelity imagery. The performance of the recommended techniques were evaluated by using mean square error and signal-to-noise ratio between the original and the bandwidth compressed imagery, subjective quality of single frames after bandwidth compression, and finally, by generating a video tape of 10 seconds of Field-Sequential Color TV imagery and before and after bandwidth compression. These results demonstrated that the recommended techniques can be used to achieve bandwidth compression for Shuttle TV systems while still maintaining high fidelity in the reconstructed imagery.

### 5.2 RECOMMENDATIONS

#### 5.2.1 Recommended Systems

The TV systems considered in the study are the Field-Sequential and NTSC color TV systems for downlink transmission and slow scan high resolution system for uplink transmission. We have recommended a bandwidth compression technique for each system that meets the Shuttle requirements and their characteristics are summarized in Table 5-1. The operation of each bandwidth compression system is summarized below.

##### 5.2.1.1 Field-Sequential Color TV Data Compression System

The recommended data compression technique for the Field-Sequential Color TV system first samples and digitizes each field at a spatial resolution of 256 lines per field and 512 samples per line. The green field is then encoded using a 2D-DPCM system at 3 bits per sample. The chrominance signals are generated by subtracting green from the red and the blue fields, respectively.

The chrominance signals are then desampled and are encoded using the same 2D-DPCM system at 2 bits per sample. The proposed technique requires a memory to store one-half of the green field and a rate buffer at the output of the encoder. The resulting outputs bit rate for the encoder is about 13 Mbps. It requires a total of 60 watts of secondary power and can be built using less than 350 IC's.

Table 5-1. Characteristics of Recommended Bandwidth Compression Techniques

TV System	Algorithm Description	Bandwidth of the Compressed Signal (megabits/sec)	Compression Ratio	Power (watts)	No. of Parts
Field-Sequential Color TV System	G, R-G, and B-G are encoded using 2D-DPCM	13.1	4.8	60 <sup>+</sup>	348 <sup>+</sup>
	G, R, B are encoded using 2D-DPCM	24	2.66	27 <sup>+</sup>	85 <sup>+</sup>
NTSC Color TV System	Y, I, and Q (I and Q subsampled 5:1) are encoded using 2D-DPCM	28	6.7	30 <sup>+</sup>	100 <sup>+</sup>
Slow-Scan Uplink System	Coding by Shipping White 2D HCK code is used	0.144	3	19 <sup>*</sup>	102 <sup>*</sup>

+ - Encoder

\* - Decoder

The performance of the proposed technique was demonstrated by encoding 10 seconds of video data generated by a Field-Sequential Color camera. A side-by-side display of the original and the encoded video data demonstrated the performance of the proposed encoder at a compression ratio of about 4.8 to 1.

An alternative system, that requires only 27 watts of power, is one that uses a 2D-DPCM encoder to operate on the red, green, and blue fields directly. To maintain the same signal fidelity as that of the proposed technique, the 2D-DPCM encoder requires 3 bits per sample for encoding with an output bit rate of 24 Mbps.

#### 5.2.1.2 NTSC Color TV Data Compression System

The recommended NTSC color TV data compression technique operates on the demodulated Y, I and Q signal components. The bandwidth of illuminance signal (Y) is reduced by encoding it with a 2D-DPCM loop at 3 bits per sample. The chromaticity signals are desampled by a factor of 5 to 1 and are encoded by the same 2D-DPCM encoder at 3 bits per sample. Further bandwidth compression is achieved by transmitting I or Q alternately for each line. For each line, either I or Q is restored at the receiver by interpolating between the previous and the future lines. The transmission of the illuminance signal occurs during the active duration of the signal while transmission of I and Q takes place during the flyback period. The system produces a data rate of 28 Mbps. It can be designed using less than 60 IC's and requires less than 20 watts of secondary power for its operation.

#### 5.2.1.3 Slow-Scan Uplink Data Compression System

The recommended technique for bandwidth compression of the slow-scan system uses a two-dimensional HCK code. The image is divided into blocks of 4 x 4 samples. A code word of "0" is used to encode blocks of all white samples while a code word of "1" followed by the actual grey levels of the samples in the block is used to encode the other blocks. The decoder of the uplink system requires 19 watts of power for its operation and can be built using 102 IC's.

If one wishes to encode images with black backgrounds, such as the "Galaxie" scene, the scheme for data encoding can be revised where the "0" code word represents a block of all black samples. In this manner, the encoding system would have two modes of operation and the decoder could be configured at the beginning of a frame to handle either type of data.

#### 5.2.2 Recommendations for Future Activities

We recommend that a prototype data compression unit be built around the 2D-DPCM technique which operates at real-time TV rates. The bread-board design can be used with the Field-Sequential Color camera and a modified display system to test the performance of the proposed bandwidth compression system under various conditions that affect its coding performance. These include different lighting conditions, camera

angles, distances of the subjects from the camera, different subject color composition, and various degrees of subject motion. The main component of the proposed breadboard encoder is the 2D-DPCM system which then can be used to evaluate the performance of the second recommended system for Field-Sequential Color TV. With small modifications, the 2D-DPCM module can be integrated into a bandwidth compression system to evaluate the performance of the recommended bandwidth compression technique for real-time NTSC Color TV signals. These tests, under controlled conditions, could give a realistic and accurate evaluation of the on-board performance of the recommended encoders.

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